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This research examined time-related changes in movement mechanics of the lower extremity and performance during a soccer match simulation individualized to the subject's fitness level. Twenty-four elite amateur soccer players (12 males and 12 females) participated in two testing sessions. The first test session consisted of subjects performing the Yo-Yo Intermittent Recovery Test Level 1(YYIR1) that was used to prescribe the five sub-maximal running intensities for the soccer match simulation performed during test session two. The average distance run during the YYIR1 test was 1780 ±619.23 meters resulting in a match simulation running distance of 10165.52 ±1001.69 meters. Analysis of the progressive change during the soccer match simulation revealed time-related increases and changes in the rate of increase in RPE, and performance decrements across halves in sprinting, and dominant and non-dominant limb cutting with soccer match simulation duration. In contrast, a lack of significant time-related change was observed for squat jump, modified counter movement jump height, and lower extremity vertical stiffness and impedance in both the dominant and non-dominant limbs during a complex jumping task.

The primary findings are that an individualized soccer match simulation prescribed using YYIR1 performance successfully replicates the demands of a soccer match, and resulted in time-related increases in RPE accompanied by decrements in sprinting and cutting speed with increasing match simulation duration. The lack of time-related change in jump performance and movement mechanics demonstrates the need for

further analyses of the execution of complex tasks and the modulation of lower extremity coordination that allowed for maintenance of performance and movement mechanics during soccer match simulated exercise.

THE EFFECT OF AN INDIVIDUALIZED SOCCER MATCH SIMULATION ON MOVEMENT AND PERFORMANCE

By

John R. Cone

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The Faculty of The Graduate School at
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Approved by

Committee Chair

To my wife and best friend, Cindy:

I can never express my gratitude for your love, support, companionship, understanding, and patience. Thanks for making me laugh.

To my Mom, Sister, and Brother:

Thanks for the guidance, support, and love.

To my Dad, and BonneMa:

Dad, I think you would have enjoyed this venture, and BonneMa, I think you would enjoy the celebration upon its completion. Thanks for the lessons and know that you continue to motivate me. You are both missed and loved.

APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Time loss injuries in soccer occur at a rate greater than one injury per player during a single season (Hagglund, Walden, & Ekstrand, 2003; Hawkins & Fuller, 1999; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001), with the rate being 5 (Hagglund et al., 2003; Walden, Hagglund, & Ekstrand, 2005a) to 12 times (Morgan & Oberlander, 2001) greater in competition than in training. Non-contact injuries in soccer contribute to as many as 55% (A. Junge, Chomiak, & Dvorak, 2000) to 59% (Hawkins & Fuller, 1999) of the total injuries in youth and professional players, respectively. Further, non-contact injuries are more severe than contact injuries as they consistently result in more time loss (Chomiak, Junge, Peterson, & Dvorak, 2000; A. Junge, Dvorak, & Graf-Baumann, 2004; Kofotolis, Kellis, & Vlachopoulos, 2007) with 88% of non-contact injuries resulting in time loss compared to 59% of contact injuries (A. Junge, Dvorak, & Graf-Baumann, 2004). The primary actions at the time of non-contact injury are running (Hawkins & Fuller, 1999; Hawkins et al., 2001; Woods et al., 2004), twisting or turning (Hawkins & Fuller, 1999; Hawkins et al., 2001), jumping (Hawkins et al., 2001), and landing (Hawkins & Fuller, 1999). The risk associated with these injuries appears to increase with match duration (Hawkins & Fuller, 1999; Hawkins et al., 2001; Price, Hawkins, Hulse, & Hodson, 2004) as physical performance is declining (Bangsbo, 1994b;

Bangsbo, Norregaard, & Thorso, 1991; Mohr, Krustrup, & Bangsbo, 2003; Reilly & Thomas, 1976; Stroyer, Hansen, & Klausen, 2004; Tumilty, 1993). Together these findings suggest that decrements in movement mechanics and performance as a function of soccer match duration may contribute to the increase in injury that occurs with match duration, and that training factors (thus modifiable factors) may play a role in injury risk and severity.

The primary means for analyzing the effect of a soccer match on movement mechanics and performance have been exercise protocols that simulate the physiological demands of a soccer match. These studies have incorporated either steady state or intermittent exercise protocols performed via treadmill and shuttle running, as well as cycle ergometry. Research has demonstrated that strength (M. P. Greig, McNaughton, & Lovell, 2006; Mercer, Gleeson, & Wren, 2003; Rahnama, Reilly, Lees, & Graham-Smith, 2003), jump performance (Oliver, Armstrong, & Williams, 2008), muscle activity (M. P. Greig et al., 2006; Oliver et al., 2008; Rahnama, Lees, & Reilly, 2006), and cutting (M. Greig, 2009; Sanna & O'Connor, 2008) are negatively affected by soccer match simulated exercise. However, there are several additional methodological considerations that should be addressed when designing a soccer match simulation in order to effectively replicate the physiological and mechanical, i.e. movement, demands of a soccer match. Specifically, those components thought to be integral to physical soccer match performance that should be reflected in these designs are: 1) the highly intermittent nature of soccer and the complete spectrum of running intensities: standing, walking, jogging, and low, moderate, and high-speed running, as well as sprinting, 2) a high level of stretch shortening cycle (SSC) actions that are paramount to locomotion in soccer and accompanies fluctuation in running speed, 3) incremental analysis of mechanical decrements in movement performance that accompany SSC demands specific to the duration of soccer match, and 4) the contribution of fitness level to physical match performance. Although some of these components are addressed in existing protocols, no single protocol has yet to address all of these components.

Of primary concern is the need to individualize physical match simulation performance to the individual's fitness level, as a positive correlation has been found between fitness level and physical performance as measured by total distance covered (Reilly & Thomas, 1976; Sanna & O'Connor, 2008; Smaros, 1980), and distance covered at high intensity and sprinting (Mohr et al., 2003) in match analyses. Moreover, previous soccer match simulations have focused primarily on pre- and post-test designs, which lack progressive analyses of movement that may better elucidate the performance changes during match duration in a way that mirrors the reported increase in injury risk during a soccer match (Hawkins et al., 2001; Price et al., 2004). Finally, no study has examined the effect of simulated soccer match duration on the three primary actions that have been associated with non-contact injury in soccer: running, twisting or turning, and jumping and landing (Hawkins & Fuller, 1999; Hawkins et al., 2001; Woods et al., 2004). Hence, improving soccer match simulation protocols to address these concerns will allow for understanding of potential changes in physical performance and movement to the change in injury rates observed as a match progresses.

It has also been suggested that changes in movement mechanics are a likely contributor to the increase in injury that occurs with soccer match duration (M. P. Greig et al., 2006). This speculation is supported within soccer simulation research which indicates that actions containing a high stretch-shortening cycle (SSC) component, such as sprinting, cutting, and jumping, result in greater changes in performance (Oliver et al., 2008) and that changes in movement mechanics, such as increases in electromechanical delay and anterior knee joint laxity are more affected by exercise with a higher SSC component (Gleeson, Reilly, Mercer, Rakowski, & Rees, 1998). Given the highly intermittent nature of soccer with over 1100 changes in locomotion at a mean duration of 4.5s (Bangsbo, 1994b; Bangsbo et al., 1991), the SSC demands are immense and should be accounted for in any soccer match simulation protocol.

In this regard, measures of vertical and lower extremity joint stiffness have often been used to characterize the effects of SSC exercise (Dutto & Smith, 2002; Hunter & Smith, 2007; Kuitunen, Kyrolainen, Avela, & Komi, 2007; Toumi et al., 2006). Stiffness has been defined as the body’s resistance to deformation (Brughelli & Cronin, 2008a), and consists of a passive component provided by ligaments and tendons, and an active muscular component (Arampatzis, Schade, Walsh, & Bruggemann, 2001). Studies have demonstrated that a decrease in vertical stiffness often accompanies acute and prolonged SSC work (Dutto & Smith, 2002; Kuitunen et al., 2007; Moran & Marshall, 2006b), and is indicative of a decreased neuromuscular capacity to control movement (Dutto & Smith, 2002; Kuitunen et al., 2007; Toumi et al., 2006). This decrease in stiffness is speculated to result in a decrease in dynamic stability (Hughes & Watkins, 2008) resulting in a corollary increase in the amount of stress placed on the body's passive components, thereby increasing the likelihood of injury (Dutto & Smith, 2002). The effect which soccer match duration may have on movement mechanics, specifically changes in stiffness is not well understood. An examination of performance and movement decrements during a soccer match simulation that better accounts for the physiological and SSC movement demands of the sport, is individualized to the participant's soccer-specific fitness level, and incorporates a progressive analysis of movement and performance, may better characterize the relationship between soccer match duration and changes in movement mechanics.

Statement of the Problem

Injury in soccer has been shown to occur more frequently in competition than training (Hagglund et al., 2003; Morgan & Oberlander, 2001; Walden et al., 2005a), with non-contact injuries consistently more severe (Chomiak et al., 2000; A. Junge, Dvorak, & Graf-Baumann, 2004; Kofotolis et al., 2007). The increase in injury incidence with soccer match duration (Hawkins & Fuller, 1999; Hawkins et al., 2001; A. Junge, Dvorak, & Graf-Baumann, 2004; Kofotolis et al., 2007; Price et al., 2004) and accompanying decrease in physical performance (Bangsbo, 1994b; Bangsbo et al., 1991; Mohr et al., 2003; Reilly & Thomas, 1976; Stroyer et al., 2004; Tumilty, 1993) has resulted in speculation that changes in neuromuscular performance and movement mechanics may contribute to the increase in injury risk that has been documented to occur with soccer match duration.

The primary method for analyzing the effects of a soccer match has been treadmill and shuttle running simulations. These studies have addressed a number of likely contributors to increasing injury risk and performance decrements. However, no study has yet to individualize physiological demands, effectively simulate movement demands of a soccer match, and integrate incremental analyses in a way that mirrors the findings of soccer injury research. Systematically examining changes in performance and movement during an individualized match simulation protocol will allow us to gain a better understanding of the progressive effects of soccer match duration on movement mechanics. Therefore, the primary purpose of this study was to examine progressive changes in exertion, performance in sprinting, cutting, and jumping, and movement mechanics in jumping and landing during the course of an individualized soccer match simulation designed to address the physiological and SSC movement demands of a competitive soccer match.

Objective and Hypotheses

The primary objective of this study was to determine if lower extremity function was adversely affected by exercise duration during a soccer match simulation protocol.

Specifically, the research investigated the effects of exercise duration on changes in exertion level, performance during cutting and sprinting, and performance and movement mechanics while jumping and landing. The overall hypothesis was that exertion, performance, and movement would decrease in a progressive manner with soccer match duration. Specifically, the following hypotheses were examined.

***Hypothesis 1*:** Rating of perceived exertion will increase with soccer match simulation duration.

- Hypothesis 1a: The increase in rating of perceived exertion would be greater in the second half than the first half, and there would be a faster rate of increase towards the end of each half of play.

***Hypothesis 2*:** Sprint and cutting speed, as well as modified counter movement jump height would decrease with soccer match simulation duration.

- Hypothesis 2a: The decrease in sprint and cutting speed, and modified counter movement jump height would be greater in the second half than the first half, and there would be a faster rate of change towards the end of each half of play.

***Hypothesis 3*:** Squat jump height would remain stable during the soccer match simulation.

***Hypothesis 4*:** Lower extremity vertical stiffness during landing and jumping would decrease significantly with match simulation duration.

- Hypothesis 4a: The decrease in vertical stiffness would be greater in the second half than the first, and there would be a faster rate of decline towards the end of each half of play.

***Hypothesis 5*:** Lower extremity vertical impedance during single-leg landing would decrease significantly with match simulation duration.

- Hypothesis 5a: The decrease in vertical impedance would be greater in the second half than the first, and there would be a faster rate of decline towards the end of each half of play.

Assumptions and Limitations

1. The physical demands of a soccer match may be effectively simulated via intermittent exercise replicating the activity pattern, intensity, duration, and structure of a soccer match.
2. The individualized soccer match simulation replicates the participant's physical performance during an actual soccer match.
3. Positional differences in activity pattern during a soccer match are minimal.
4. Participants reached and maintained maximal effort during all testing components.
5. Results of this study cannot be generalized beyond the participants' playing level and age.

6. Lower extremity stiffness and impedance measures during the integrated jump task are effectively represented by a spring-mass model.
7. Movement during the integrated jump task occurs primarily in the sagittal plane and was effectively measured via two-dimensional kinematics.
8. Reductions in vertical stiffness, impedance, squat jump and modified counter-movement jump height, and cutting and sprint speed during the match simulation can be reasonably attributed to soccer simulated exercise demands.

Delimitations

1. Participants were currently competitive, injury free soccer players at the collegiate, elite club, or professional level.
2. Participants had no history of lower extremity surgery.
3. Two-dimensional kinematic and kinetic analysis of the jump task used to characterize lower extremity stiffness was a valid and reliable measure.

Operational Definitions

Stretch-Shortening Cycle: Movement involving alternately an eccentric muscle action, followed by concentric muscle action.

Vertical leg stiffness: Characterizes the body’s resistance to vertical forces acting on the body’s center of mass in SSC actions, calculated as the vertical displacement of the body’s center of mass relative to the maximal vertical ground reaction force (vGRF).

Vertical leg impedance: Characterizes the body's resistance to vertical forces acting on the body's center of mass during deceleration in eccentric muscle action, calculated as the vertical displacement of the body's center of mass relative to the maximal vGRF.

Integrated jump task: A three phase sequential jump task involving: 1) a squat jump (concentric), followed by 2) a modified counter-movement jump (SSC), and a 3) single-leg landing (eccentric).

Squat jump: A maximal vertical jump performed from an isometric squat position at approximately 90 degrees of knee flexion.

Modified counter movement jump: Jump task consists of landing from the squat jump immediately followed by a maximal jump upon landing.

505 Agility Test: 15 meter shuttle run incorporating a single unilateral cutting task.

Sprint performance: The running speed ($m \cdot s^{-1}$) during the final 10-meters of the 505 agility test.

Agility performance: The running speed ($m \cdot s^{-1}$) during the 5-meters surrounding cutting during the 505 agility test.

Jump performance: The jump height (meters) achieved during the respective jump, squat jump and modified counter movement jump, during the integrated jump task.

Dominant limb: Defined as the stance limb when kicking a soccer ball.

Non-dominant limb: Defined as the preferred limb when kicking a soccer ball.

Statistical model abbreviations: The following abbreviations are used in the statistical modeling to examine time-related change during the match simulation.

- π_{0i}: Characterizes the initial value at the start of half one, also termed the intercept.
- $\pi_{1i}(time)$: Characterizes the change occurring at the start of half one.
- $\pi_{2i}(time2)$: Characterizes the rate of change during half one.
- $\pi_{3i}(D)$: Characterizes the difference between the initial value at the start of half two (post-half-time) relative to the start of half one.
- $\pi_{4i}(D * time)$: Characterizes the difference in change at the start of half two compared to the start of half one.
- $\pi_{5i}(D * time2)$: Characterizes the difference in the rate of change during half two compared with half one.

CHAPTER II

LITERATURE REVIEW

The purpose of this dissertation was to characterize the progressive changes in movement mechanics and performance during the course of an individualized soccer match simulation. Specifically, this research quantified changes in vertical stiffness during a modified counter movement jump and vertical leg and joint impedance during landing (measurements of movement mechanics), and decrements in jump height and running speed during sprinting and cutting (measures of performance). This literature review will examine: 1) the nature and characteristics of injury in soccer, 2) physical soccer match demands and the role of fitness in match performance, 3) soccer match simulation research related to performance and injury risk factors, and 4) the nature of SSC fatigue in soccer and its effect on lower extremity stiffness.

The Nature and Characteristics of Injury in Soccer

During the course of a single soccer season, 86 to 100% of professional players sustain a time loss injury (Hawkins & Fuller, 1999), with a single season average of 1.3 (Hawkins et al., 2001) to 2.3 (Hagglund et al., 2003) injuries per player. Comparison of injury characteristics over time (Hagglund et al., 2003), region (A. Junge et al., 2000), and player age (Hawkins et al., 2001; Merron, Selfe, Swire, & Rolf, 2006; Price et al., 2004) show a large degree of stability across populations. This consistency is most evident when comparing injury severity between youth (Price et al., 2004) and adult professional (Hawkins et al., 2001) players in the same environment and culture, where there is little difference in injury characteristics and mean number of days missed, 21.9 vs 24.2, respectively. Moderate injuries, which occur at the greatest rate, comprise 29 (Hawkins et al., 2001) to 45% (Walden, Hagglund, & Ekstrand, 2005b) of all reported injuries, with a mean time loss of 13.8 (Walden et al., 2005b) to 24.2 (Hawkins et al., 2001) days per injury. Analysis of injury over 20 years time indicate that there has been an increase in moderate injuries while the number of severe injuries remained stable (Hagglund et al., 2003). This speculatively indicates that training and injury prevention in soccer has not progressed significantly as to positively affect injury rate and incidence.

The majority of injuries in soccer are consistent with the nature of soccer and occur to the lower extremity (Agel, Evans, Dick, Putukian, & Marshall, 2007; Dvorak & Junge, 2000; Dvorak, Junge, Grimm, & Kirkendall, 2007; Ekstrand & Gillquist, 1983; Ekstrand, Gillquist, Moeller, Oeberg, & Liljedahl, 1983; Ekstrand & Tropp, 1990; Hagglund et al., 2003; Hagglund, Walden, & Ekstrand, 2005; Hawkins & Fuller, 1996, 1999; Hawkins et al., 2001; A. Junge, Cheung, Edwards, & Dvorak, 2004; Astrid Junge & Dvorak, 2004; A. Junge, Dvorak, & Graf-Baumann, 2004; A. Junge, Dvorak, Graf-Baumann, & Peterson, 2004; Morgan & Oberlander, 2001; Price et al., 2004; Walden et al., 2005a, 2005b; Witvrouw, Danneels, Asselman, D'Have, & Cambier, 2003; Woods, Hawkins, Hulse, & Hodson, 2002). The thigh, knee, and ankle are the most frequently injured sites, followed by the lower leg and groin (Agel et al., 2007; Dvorak et al., 2007; Hawkins & Fuller, 1999; Hawkins et al., 2001; A. Junge, Cheung et al., 2004; Price et al., 2004; Walden et al., 2005a). Non-contact mechanisms of injury account for 27 (Dvorak et al., 2007; A. Junge, Dvorak, & Graf-Baumann, 2004) to 59% (Hawkins & Fuller, 1999) of all injuries in professionals, and 34 (Price et al., 2004) to 55% (A. Junge et al., 2000) of all injuries in youth soccer players. Non-contact injuries appear to represent the majority of severe injuries (Chomiak et al., 2000; Kofotolis et al., 2007), as these injuries are reported to result in greater time loss than contact injuries (Chomiak et al., 2000). The primary actions contributing to non-contact injury are running, twisting or turning, and jumping or landing (Hawkins & Fuller, 1999; Hawkins et al., 2001; Price et al., 2004; Woods et al., 2002; Woods et al., 2004). These findings, that non-contact injuries are more severe and occur with equal to greater frequency than contact injuries, suggest that the majority of severe injuries are preventable. As such, modifiable factors that may contribute to the increase in injury need to be examined so that these components can be specifically targeted in training.

Competition Versus Training Injury

It has been consistently demonstrated that injury in soccer occurs at a higher rate during competition than training (Agel et al., 2007; Hagglund et al., 2003; Hawkins & Fuller, 1999; Hawkins et al., 2001; Morgan & Oberlander, 2001; Price et al., 2004). Analysis of injury rate per 1000 hours of exposure demonstrates that match injury rate is 5 (Hagglund et al., 2003; Walden et al., 2005a) to 12 times (Morgan & Oberlander, 2001) higher than that observed in training. This difference is greatest in the American professional league (Major League Soccer), where a 12-fold greater injury rate was observed in competition relative to training (Morgan & Oberlander, 2001). When injury severity, location, and diagnosis are expressed relative to their occurrence during training or competition, injury location and severity are stable, while injury diagnosis differs (Hawkins & Fuller, 1999; Hawkins et al., 2001; Price et al., 2004). Specifically, muscle strain occurs more frequently in training than competition, while ligamentous strain/rupture, contusion, and bone fractures occur more frequently in competition (Table 1) (Hawkins & Fuller, 1999; Hawkins et al., 2001; Price et al., 2004). The greater rate of traumatic joint and bone injury suggest that players may perform at a higher intensity in competition versus practice.

Injury Rate and Soccer Match Duration

A consistent finding when analyzing injury risk in soccer is an increase in the incidence of injury with match duration (Hawkins & Fuller, 1999; Hawkins et al., 2001; A. Junge, Dvorak, & Graf-Baumann, 2004; Kofotolis et al., 2007; Price et al., 2004). Studies report a 9 (Price et al., 2004) to 18% (Hawkins & Fuller, 1999; Hawkins et al., 2001) increase in injuries during the second half compared to the first. Further, analysis of match injury rates in 15-minute segments reveals that the greatest number of injuries occur in the final 15-minutes of each half in youth players (Price et al., 2004), while the greatest number of injuries occurred in the final 15-minutes of play in professional players (Hawkins & Fuller, 1999; Hawkins et al., 2001). Professional players also had significantly more injuries during the final 15-minutes of the first half, and the latter 30-minutes of the second half of play (Hawkins & Fuller, 1999; Hawkins et al., 2001). Risk of severe ankle injuries shows the greatest increase with match duration. In one report, 68% of the total number of injuries occurred in the final 15-minutes of each half, and the rate of injury was 10% higher in the final 15-minutes of the second half compared to the final 15-minutes of the first (Kofotolis et al., 2007). This rise in injury with soccer match duration suggests that lower extremity function may be compromised as match duration progresses, leading to an increase risk of injury.

Table 1: Injury diagnosis during training and competition.

(Bold = expressed as a percentage of the number of injuries observed during training or competition. *Italics* = expressed as a percentage of the total number of injuries observed). [*= composite of muscle contusion and tissue bruising.]

Researchers	Population	Country of Study	Injury Occurrence	Muscle strain/rupture		Ligamentous sprain/rupture		Contusion*		Fracture	
Hawkins et al. (Hawkins et al., 2001)	Professional	England	Training	**42**	*14*	**18**	*6*	**7**	*2*	**3**	*1*
			Competition	**35**	*22*	**20**	*13*	**16**	*10*	**5**	*3*
Price et al. (Price et al., 2004)	Youth Academy	England	Training	**33**	*16*	**20**	*10*	**11**	*5*	**4**	*2*
			Competition	**29**	*15*	**22**	*11*	**20**	*10*	**4**	*1*
Hawkins and Fuller (Hawkins & Fuller, 1999)	Professional	England	Training	**53**	*17*	**18**	*6*	**5**	*2*	**4**	*1*
			Competition	**37**	*25*	**14**	*14*	**24**	*16*	**4**	*3*
Hawkins and Fuller (Hawkins & Fuller, 1999)	Youth Academy	England	Training	**53**	*18*	**19**	*7*	**16**	*5*	**2**	*<1*
			Competition	**28**	*18*	**20**	*13*	**32**	*21*	**6**	*3*

Physical Soccer Match Demands and Match Performance

The very nature of soccer (e.g. match duration and field size), endorses a high level of physical demand. Soccer match demands are most simply characterized by total distance covered or mean intensity. In more detailed analyses, match demands have been analyzed via distance covered across a spectrum of six intensities: standing, walking, jogging, low-intensity, moderate-intensity, and high- intensity (Krustrup, Mohr, Ellingsgaard, & Bangsbo, 2005; Mohr et al., 2003). Recent analyses report that male professional players run between 10 and 13 km (Bangsbo, Mohr, & Krustrup, 2006), while female elite professionals cover 9.7 to 11.3 km (Krustrup et al., 2005). Fatigue has been shown to occur as a function of match duration as measured by a decrease in distance run in the second half compared to the first (Bangsbo, 1994b; Bangsbo et al., 1991; Reilly & Thomas, 1976; Stroyer et al., 2004; Tumilty, 1993), and in significantly less total distance covered in the final 15-minutes of each half compared with all previous 15-minute segments (Mohr et al., 2003). Fatigue is most evident during the final 15-minutes of play where a 34% (Krustrup et al., 2005) and a 45% decrease (Mohr et al., 2003) in high-intensity running has been observed in female and male professionals, respectively, compared to the first 15-minutes of the match. Additionally, sprint performance compared across the same time points decreased by 43% in male professionals (Mohr et al., 2003). These decrements in physical performance during the course of a match, at time periods consistent with an increased rate of injury with match duration (Hawkins & Fuller, 1998; Hawkins et al., 2001; Astrid Junge & Dvorak, 2004;

Kofotolis et al., 2007; Price et al., 2004), suggests there may be a strong tie between fatigue and increasing injury rate with soccer match duration.

Fitness Level and Soccer Match Performance

The contribution of fitness level to physical performance during a soccer match is extensively documented (Bangsbo, 1994b; Bangsbo et al., 2006; Bangsbo et al., 1991; Helgerud, Engen, Wisloff, & Hoff, 2001; Krustrup et al., 2005; Mohr et al., 2003; Mohr, Krustrup, & Bangsbo, 2005; Reilly & Thomas, 1976; Smaros, 1980). The relationship between fitness level and match performance is most frequently observed as the positive correlation between a player's maximal oxygen uptake (VO_{2max}) and the total distance covered during a match (Reilly & Thomas, 1976; Smaros, 1980). More recently a positive correlation between VO_{2max} and high intensity running and sprinting, and the number of involvements a player has with the ball during the course of the match has also been observed (Helgerud et al., 2001; Mohr et al., 2003). In comparing level of play, the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1), a modification of a graded exercise test comprised of 20-meter shuttle running performed at increasing running speeds with 10s recovery intervals, was used by Mohr et al. (Mohr et al., 2003). Performed to until the pace dictated can no longer be maintained, higher level professionals performed significantly better on the YYIR1 than their lower level counterparts, running 11% further in the graded exercise test (Mohr et al., 2003). This difference in YYIR1 test performance is consistent with match performance, where top level professionals cover 5% greater total distance than moderate level professionals (10.86 ±0.18 km vs. 10.33 ±0.26km), as well as 28% and 58% greater distances in high intensity running and sprinting, respectively (Mohr et al., 2003). This observation is consistent with the findings that YYIR1 performance in male professionals is positively correlated to total distance run, the amount of high-intensity running, and combined high-intensity and sprint distance during a match (Mohr et al., 2003). Analysis in female professionals demonstrated that the amount of high-intensity running during the final 15-minutes of each half was significantly correlated (r=0.83) to YYIR1 performance (Krustrup et al., 2005). The effect of increasing fitness on match performance is further exemplified by intervention studies where increases in physical fitness, quantified as a 10.8% increase in VO_{2max}, resulted in a 20% increase in total distance covered during a match, a 100% increase in the total number of sprints, and a 24% increase in the number of involvements with the ball (Helgerud et al., 2001).The increased ability to maintain intensity during the match is also evident in greater average match heart rates (HR_{ave}), expressed as a percentage of maximal heart rate (HR_{max}), and a decreased difference in HR_{ave} between the second and first halves of play (Helgerud et al., 2001). Together these observations indicate that fitness level is inextricably tied to a players physical match performance and is largely responsible for inter-individual differences in physical match performance.

Soccer Match Simulation Research and Performance and Injury Risk Factors

Due to the logistical challenges in directly analyzing the effects of a soccer match, direct analyses are limited. Following participation in an actual soccer match, subjects in these studies have demonstrated no significant change in squat jump (Hoffman, Nusse, & Kang, 2003) and counter-movement jump performance (Hoffman et al., 2003; Thorlund, Aagaard, & Madsen, 2009), but a 7 and 11% reduction in peak muscle torque of the hamstring and quadriceps muscles, respectively (Thorlund et al., 2009). Several practical challenges persist in this type of analyses, foremost is that no study has quantified the amount of work that was performed during the course of the match. In the study by Hoffman et al. (Hoffman et al., 2003) the problems accompanying direct analysis are accentuated by a substitution pattern that resulted in the studied players varying in both the amount of time played, and the time elapsed between cessation of play and post-match testing. To control for these factors, the primary means of analysis has been soccer match simulations designed to replicate the physiological demands of soccer. These studies have consisted of treadmill and shuttle running protocols, as well as cycle ergometry (Gleeson et al., 1998; M. Greig, 2008; M. P. Greig et al., 2006; M.P. Greig & Walker-Johnson, 2007; Mercer et al., 2003; Oliver et al., 2008; Rahnama et al., 2006; Rahnama et al., 2003; Sanna & O'Connor, 2008). Using a variety of populations, protocols, and mode of exercises, these studies have addressed the role of soccer simulated exercise duration and have consistently documented decrements of strength, muscle activation, performance, and movement mechanics (Table 2).

Table 2: Soccer simulations and primary findings.

Researchers	Population	Protocol Type	Primary Findings (pre- to post-testing)
Gleeson et al. (Gleeson et al., 1998)	Male Recreational	Treadmill and Shuttle Running	• Comparison of shuttle and continuous treadmill running revealed the following: o Greater decrease in isokinetic hamstring (11% v 4%) and quadriceps (20% v 4%) peak torque at $60°\cdot s^{-1}$ from intermittent shuttle running compared to continuous treadmill running, respectively. o Greater increase in anterior knee joint laxity (44% v 24%) from intermittent shuttle running compared to treadmill running, respectively. o Greater increases in blood lactate from intermittent shuttle running.
Rahnama et al. (Rahnama et al., 2003)	Male University	Treadmill	• Decrease in peak isokinetic concentric (60, 120, and $300°\cdot s^{-1}$) and eccentric quadriceps ($120°$ $rad\cdot s^{-1}$) torque from pre- to post-exercise. • Decrease in peak isokinetic concentric (60, 120, and $300°\cdot s^{-1}$) and eccentric hamstring ($120°\cdot s^{-1}$) torque from pre- to half-time, half-time to post-exercise, and pre- to post-exercise. • Decrease in concentric and eccentric hamstring to quadriceps ratio across three velocities 60, 120, and $300°\cdot s^{-1}$ of 3.6, 9.7, and 6.2% (kicking limb) and 3.4, 7.9, and 3.7% (stance limb), respectively.
Mercer et al. (Mercer et al., 2003)	Male University	Intermittent Cycling	• Decrease in isokinetic hamstring peak torque (1.05 $rad\cdot s^{-1}$) from pre- to post-exercise in males of 22.3% and females of 24.9%.
Rahnama et al. (Rahnama et al., 2006)	Male University	Treadmill	• Decrease in surface muscle activity (quantified via RMS) during running for the rectus femoris, biceps femoris, and tibialis anterior from pre- to half-time, and pre- to full-time was observed • Decreases in surface muscle activity were significantly greater as running speeds increase, with greatest difference at 21 $km\cdot h^{-1}$ compared to lower running velocities of 15, 12 and 6 $km\cdot h^{-1}$.
Greig et al. 2006 (M. P. Greig et al., 2006)	Male Semi-Professional	Treadmill Running	• Increase in RPE and HR with exercise duration in soccer-simulated treadmill running and steady state running. • Surface muscle activity of rectus femoris and biceps femoris (quantified as total and peak EMG activity) revealed that only peak EMG of the rectus femoris increased with exercise duration for both protocols. • Comparison of steady state and soccer-simulated running showed a significant difference between protocols for RPE during the first 30-minutes of exercise only, and no significant difference in HR throughout.

Greig et al. 2007 (M.P. Greig & Walker-Johnson, 2007)	Male Semi-Professional	Treadmill Running	• No difference in stability index measured via a stabilometer during single-leg balance was observed for soccer match simulation duration. • Directional analysis of single-leg balance revealed that deflection in the anterior direction increased significantly with exercise duration.
Greig 2008 (M. Greig, 2008)	Male Semi-Professional	Treadmill	• Concentric isokinetic peak quadriceps and hamstring torque was maintained across all velocities (60, 180, and $300°\cdot s^{-1}$). • Eccentric isokinetic peak torque of the hamstrings occurred at the two highest velocities from pre- to post-exercise ($180°\cdot s^{-1}$ of 20.1% and $300°\cdot s^{-1}$ of 23.9%). • Decrease in dynamic strength ratio (eccentric hamstring torque to concentric quadriceps torque) was observed from pre- to post-exercise at $180°\cdot s^{-1}$ (105% to 81%), and $300°\cdot s^{-1}$ (133% to 103%). ○ Recovery from passive half-time was insufficient to facilitate recovery to pre-exercise levels.
Oliver et al. (Oliver et al., 2008)	Male Adolescent	Non-motorized treadmill	• No change in peak and mean sprint velocity was observed. • Decrease in jump height was observed across squat, CMJ, and drop jumps (DJ). • Decrease in surface muscle activity (quantified as the sum of muscle activity of the vastus lateralis, biceps femoris, tibialis anterior, and soleus) was observed following exercise in the propulsive phase of the drop jump only, but not the braking or pre-activation phases of the jump.
Sanna and O’Connor (Sanna & O'Connor, 2008)	Female University	Side-Cutting	• An increase in RPE (1-10 scale) with exercise duration of 60-minutes occurred from 2.7 (pre-) to 6.8 (post-exercise). • Non-significant decrease in power output during CMJ post-exercise was observed 7%. • Only significant difference during cutting from pre- to post-exercise was observed in knee internal rotation.
Greig et al. 2009 (M. Greig & Siegler, 2009)	Male Semi-Professional	Treadmill Running	• Decrease in knee flexion and total ROM during cutting occurred across both halves: pre- (39.5°), half-time (30.57°), post half-time (37.71°), and post-exercise (30.21°). • Valgus motion during flexion while cutting increased from pre-exercise (value not reported) to the end of the first half (4.7°) and end of the 2nd half (6.9°).
Greig et al. 2009 (M. Greig & Siegler, 2009)	Male Semi-Professional	Treadmill Running	• A significant decrease in isokinetic peak hamstrings torque was observed at $300°\cdot s^{-1}$ with exercise duration from pre- to half-time (17.4%), and post-exercise (23.9%).

Treadmill soccer match simulations, utilizing a variety of protocols, have revealed a consistent decrement in isokinetic muscle strength of the quadriceps and hamstring muscles following exercise (M. Greig & Siegler, 2009; M. P. Greig et al., 2006; Rahnama et al., 2006; Rahnama et al., 2003). Strength decrements were consistent across dominant and non-dominant limbs (M. P. Greig et al., 2006; Rahnama et al., 2003), and resulted in a significant decrease in dynamic hamstring to quadriceps ratio (eccentric hamstring torque to concentric quadriceps torque) (M. Greig, 2008; Rahnama et al., 2003). The resulting strength imbalance suggests that late in a match lower extremity strength may compromise the player's ability to stabilize the knee joint effectively (M. Greig, 2008; Rahnama et al., 2003). Further, it is apparent that actions involving faster movement velocities are more highly affected by soccer match duration. This is evident in the finding that the greatest decrements in peak eccentric hamstring torque were at the highest speed tested, $300°\cdot s^{-1}$ compared to $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$, at half- and full-time (M. Greig & Siegler, 2009). This is further corroborated by the finding that muscle activity of the rectus femoris, biceps femoris, and tibialis anterior was decreased to a greater extent at higher running speeds (Rahnama et al., 2006). Additionally, it appears that lower extremity muscular imbalances may increase with movement velocity, evident via a decrease in the dynamic strength ratio with exercise duration at 180 and $300°\cdot s^{-1}$, but not at $60 deg\cdot s^{-1}$ (M. Greig, 2008).

These differences in muscle strength at higher movement velocities, and specifically decreases in muscle activation at higher running velocities, suggest that muscular performance may be more highly affected during high velocity, high SSC movements. This latter suggestion, that movements containing a high SSC component may be more susceptible to match duration, is supported by the finding that muscle activity decreased across the muscles of the shank and thigh in the drop jump, but not in counter-movement and squat jumping following treadmill running simulated soccer match demands (Oliver et al., 2008). Together, these findings indicate that muscle may be more highly affected in actions having a higher velocity with a corollary higher SSC component. Interestingly, the aforementioned changes in muscle strength (M. P. Greig et al., 2006; Rahnama et al., 2003), activation (M. Greig & Siegler, 2009; Rahnama et al., 2006) and jump performance (Oliver et al., 2008) were observed following treadmill running protocols without inclusion of SSC work as it exists in a soccer match. Hence, it is likely that greater decrements in movement mechanics and performance would be observed in match simulations which are more inclusive of movements with a high SSC component.

The lack of SSC work in treadmill running is addressed in a limited manner by Oliver et al. (Oliver et al., 2008) who used a non-motorized treadmill, and more thoroughly by Gleeson et al. (Gleeson et al., 1998) who compared three distance matched protocols simulating the physiological load of a soccer match: 1) treadmill steady state, 2) continuous shuttle running, and 3) intermittent shuttle running. The latter analysis determined that intermittent shuttle running produced the greatest increase in anterior knee joint laxity, and decrease in peak torque, while continuous shuttle running resulted in an increase in electromechanical delay (Gleeson et al., 1998). Of the metabolic measurements made, the most notable observation was that blood lactate concentration was greatest during intermittent shuttle running and decreased across the four sampled time points (Gleeson et al., 1998), an observation that is similar to analyses of blood lactate during actual soccer match-play (Krustrup et al., 2006). The documented differences between treadmill and shuttle running suggest that exercise having a greater SSC component more greatly impact mechanics of movement, as well as physiological parameters. Ultimately, these findings illustrate fundamental differences in treadmill and over-ground running, and the inability of treadmill protocols to effectively simulate soccer match demands.

Variability in Participant Fitness Level in Soccer Match Simulation Research

While Gleeson et al. (Gleeson et al., 1998) demonstrated differences between treadmill and over-ground running, a primary limitation with this study highlights a consistent short-coming of soccer match simulation research, the ability to equate demands of the soccer match simulation with participant fitness level. For example, the total distance set for the protocol, 9600-meters, is similar to the match distance of senior professional players whose VO_{2max} is approximately 60 $ml \cdot kg^{-1} \cdot min^{-1}$ (Reilly, Bangsbo, & Franks, 2000), yet the recreational athletes used in this study had a mean VO_{2max} of 48.6 ±4.5 $ml \cdot kg^{-1} \cdot min^{-1}$ (Gleeson et al., 1998). Even within a homogenous group of participants, individual differences in fitness level exist that may affect physical match performance and thereby should be accounted for in the match simulation. The least variability in fitness level documented was in male semi-professionals where a 7.6% difference in direct measurement of VO_{2max} was observed (M. Greig, 2008; M. Greig, 2009; M. Greig, Marchant, Lovell, Clough, & McNaughton, 2007; M. Greig & Siegler, 2009; M. P. Greig et al., 2006; M.P. Greig & Walker-Johnson, 2007). Others note variability in fitness level from estimated VO_{2max} via shuttle running, ranging from 9.9% in female university players (Sanna & O'Connor, 2008) to 15.3% in recreational players (Gleeson et al., 1998). Given that a 10.8% increase in VO_{2max} resulted in significant increases in match performance (Helgerud et al., 2001), and an 11% difference in YYIR1 performance is sufficient to separate professionals of high and moderate playing standards (Mohr et al., 2003), the level of variability reported within these research populations may be problematic. This highlights the need for a soccer match simulation that is individualized to the participant's fitness level to insure that each player (participant) is exposed to the same type of physiological demands experienced during match play.

Structure of Soccer Match Simulations

It has been proposed that a match simulation should directly model the activity profile of a soccer match in order to more effectively simulate soccer match demands (M. P. Greig et al., 2006). Utilizing this methodology the researchers addressed several short-comings of previous match simulations. Specifically, a more complete spectrum of running intensities were addressed: standing, walking, jogging, low speed running, moderate speed running, and sprinting. Additionally, the fluctuation in intensity during the protocol, with the activity duration of each intensity ranging between 2.0 and 7.8 seconds, was designed to more closely replicate the intensity changes observed during a soccer match (M. Greig et al., 2007; M. Greig & Siegler, 2009; M. P. Greig, 2009; M. P. Greig et al., 2006; M.P. Greig & Walker-Johnson, 2007). Finally, testing at 15-minute intervals (M. Greig, 2008; M. Greig & Siegler, 2009; M. P. Greig, 2009; M. P. Greig et al., 2006; M.P. Greig & Walker-Johnson, 2007) allowed for closer comparisons to injury audit research documenting an increase in injury rate with increasing match duration (Hawkins & Fuller, 1999; Hawkins et al., 2001; Price et al., 2004).

While these modifications have advanced soccer match simulation research, several short-comings persist. The first is inherent in the use of a treadmill and the lack of soccer-specific SSC work as previously discussed. Further, the limited rate at which a treadmill can be accelerated limits the ability to effectively fluctuate between sprinting and jogging intensities (M. P. Greig et al., 2006). Finally, the number of activity changes during these protocols (M. Greig et al., 2007; M. Greig & Siegler, 2009; M. P. Greig, 2009; M. P. Greig et al., 2006; M.P. Greig & Walker-Johnson, 2007) is well short of the 1179 (Bangsbo, 1994a) to 1529 changes in activity (Krustrup et al., 2005) documented by match analyses. In order to progress match simulation research and the understanding of functional performance changes that occur with soccer match duration, these short-comings must also be addressed.

Section Summary

The progression and improvements in match simulation research have resulted in a number of the outlined short-comings being addressed within individual studies. However, no single study has yet to address all of the aforementioned short comings in a collective manner. Specifically, it appears that six fundamental components need to be addressed within a single study in order to progress our understanding of how the demands of soccer impact movement mechanics and performance over time.

1. The highly intermittent nature of a soccer match and complete spectrum of running intensities analyzed in studies of soccer match demands: standing, walking, jogging, low speed running, moderate speed running, and sprinting.
2. The SSC action that is paramount to locomotion in soccer and accompanies fluctuations in running speed.
3. Analysis of mechanical decrements in movement performance that accompany SSC demands specific to a soccer match.
4. The contribution of fitness level and subsequent individualization of match demands.
5. Analyses of progressive decrements in performance that parallels the times of increasing injury risk reported in soccer injury audits.
6. Inclusion of actions consistent with the three primary contributors to non-contact injury: running, twisting or turning, and jumping and landing.

Addressing these collective components within a single study will allow for a more complete understanding of the relationship between soccer match duration and decrements in movement mechanics and performance.

The Effect of Exercise on Lower Extremity Biomechanics

It has been suggested that the load of a soccer match is not sufficient to result in “physiological fatigue”, but that changes in movement mechanics are more likely the causative mechanism in the increase in injury rate that is observed with soccer match duration (M. P. Greig et al., 2006). This speculation is supported within the soccer simulation research by the finding that movements with a higher SSC component are more susceptible to soccer-simulated exercise (Oliver et al., 2008), and that work comprised of greater SSC actions results in greater changes in movement mechanics (Gleeson et al., 1998). Hence, the dynamic and highly intermittent nature of soccer likely results in a high load of SSC work during match play, and therefore the potential for substantially greater changes in movement mechanics and performance than has been observed with previous treadmill match simulation protocols. Moreover, a cycle of decreasing efficiency accompanying SSC work, that leads to a decreased ability to store elastic energy resulting in yet greater inefficiency and a subsequent increased rate of decrease in movement and performance (Komi, 2000; Kuitunen et al., 2007) demonstrate the integral role of SSC actions in movement and performance. These characteristics of SSC exercise have been largely lacking in current match simulation protocols, and may contribute to the disproportionate number of injuries that occur in the final minutes of each half of play. For these reasons, the following section focuses on measurement and examination of mechanical changes that have been shown to accompany acute and prolonged SSC exercise.

Lower Extremity Stiffness and Impedance

Lower extremity movement mechanics have been characterized in a number of manners, with vertical stiffness and impedance used frequently to examine movement relating to performance and injury risk (Brughelli & Cronin, 2008b; Butler, Crowell, & Davis, 2003). Most simply, vertical stiffness and impedance characterize the body's resistance to compression relative to the vertical force applied during movement (Butler et al., 2003; Hughes & Watkins, 2008; Kulas, Schmitz, Shultz, Watson, & Perrin, 2006;

McMahon & Cheng, 1990). As such, vertical stiffness and impedance reflect the dynamic stability of the lower extremity controlled via coordination across the hip, knee, and ankle joints during movement (Hughes & Watkins, 2008), and is considered to be a summation of the individual stiffness values of the lower extremity (Butler et al., 2003; Latash & Zatsiorsky, 1993). While the ideal amount of stiffness for any given task is undetermined (Brughelli & Cronin, 2008b), relative to performance and injury it is suggested that increasing vertical stiffness and impedance result in an increase in dynamic stability leading to an increase in performance (Brughelli & Cronin, 2008b; Butler et al., 2003) and a decrease in the risk of acute soft-tissue injury (Butler et al., 2003; Granata, Padua, & Wilson, 2002). As a summation of lower extremity stiffness values, both stiffness and impedance are comprised of a passive component provided by bones, ligaments and tendons, and an active component provided by muscle (Arampatzis, Schade et al., 2001; Kulas et al., 2006). Via this definition, changes in vertical stiffness or impedance result from any single, or multiple changes to the passive and/or active components of the lower extremity. Where decreases in vertical stiffness or impedance are the result of decrements in the active component, muscle, an increase in the amount of stress placed on the passive contributors to stiffness and impedance will occur (Dutto & Smith, 2002). Thus, an exercise induced decrement in muscle function that leads to a decrease in vertical stiffness or impedance results in an increase in the amount of force that must be attenuated by the passive contributors to stiffness, foremost tendon, ligament, and cartilage (Butler et al., 2003; Granata et al., 2002; Padua et al., 2006). Speculatively, the greater stress placed on passive soft tissue components results in an increase in the likelihood that acute non-contact injury will occur (Butler et al., 2003); specifically that tendon, ligament, or cartilaginous structures will yield to the increasing forces that are being placed on them as a result of decreasing muscle function resulting from exercise.

Stretch-Shortening Cycle Exercise and Stiffness

The effect of SSC and lower extremity exercise on mechanical components of movement has been previously examined using a variety of stiffness measures (Dutto & Smith, 2002; Gollhofer, Komi, Miyashita, & Aura, 1987; Horita, Komi, Nicol, & Kyrolainen, 1996, 1999; Kuitunen et al., 2007; Morin, Jeannin, Chevallier, & Belli, 2006; Padua et al., 2006). Stiffness across lower extremity segments has been calculated in three manners: 1) joint stiffness, 2) leg stiffness, and 3) vertical stiffness (Brughelli & Cronin, 2008b). Vertical stiffness represents the most global of these measures, and in SSC actions characterizes the resistance of the lower extremity to deformation with the displacement of the body's center of mass in the sagittal plane relative to the force exerted dictating vertical stiffness (K) (Brughelli & Cronin, 2008a; Hughes & Watkins, 2008). In landing, where only absorption of force is measured, the stiffness of the body to deformation is termed impedance (K_i), and is calculated similarly to vertical stiffness as the vGRF relative to vertical displacement of the body's center of mass (Kulas et al., 2006). A number of assumptions are inherent in modeling vertical stiffness and impedance. Foremost among these is that the body stores and releases, or absorbs (the case in impedance), elastic energy allowing for conservation of energy and modulation of performance (Brughelli & Cronin, 2008b; Latash & Zatsiorsky, 1993). Second is the assumption that vertical stiffness and impedance is a summation of all lower extremity stiffness values consisting of both passive (bone, tendon, ligament, and cartilage), and active (muscular) components (Butler et al., 2003; Latash & Zatsiorsky, 1993).

In studies of SSC exercise (see results in Table 3) (Dutto & Smith, 2002; Gollhofer et al., 1987; Horita et al., 1996, 1999; Kuitunen et al., 2007; Morin et al., 2006) a decrease in stiffness (muscular, joint, and/or vertical) has been documented following prolonged (Avela & Komi, 1998a, 1998b) and exhaustive (Dutto & Smith, 2002) running, as well as following acute exercise comprised of sprinting (Morin et al., 2006), and sub-maximal drop jumps (Horita et al., 1996, 1999; Kuitunen et al., 2007). It is apparent from these studies that stiffness is controlled dually by stretch-reflex and muscle activation, with increasing activation in both instances resulting in greater stiffness values (Gollhofer, Schmidtbleicher, & Dietz, 1984; Komi, 2000; Komi & Gollhofer, 1997; Kyrolainen et al., 2005). The role the stretch-reflex plays in stiffness following exercise is perhaps best demonstrated by findings that a decrease in vertical stiffness is accompanied by an increase in stretch-reflex response time, and a decrease in the duration and magnitude of the stretch-reflex response following acute bouts of SSC work (Horita et al., 1996). Regarding muscle activation, a positive correlation between decreasing muscle activation and decreasing vertical stiffness following acute SSC work has been observed in both the soleus ($r=0.81$) and gastrocnemius ($r=0.98$) (Kuitunen et al., 2007), indicative of the direct role that muscle activation plays in modulating vertical stiffness. Additionally, change in individual muscle stiffness following prolonged running have been positively correlated with both muscle pre-activation level and short-latency stretch reflex (Avela & Komi, 1998a). Together, these findings suggest that vertical stiffness and impedance are representative of changes in muscle characteristics that are modulated during acute and prolonged bouts of exercise in order to maintain performance and control movement.

The role that muscle activity and stretch reflex activation play in stiffness is speculatively time dependent. Accordingly, initial stiffness, defined as stiffness during initial contact in landing, is the result of muscle activation, while thereafter the stretch-reflex combined with muscle activation modulate stiffness (Horita et al., 1996). Of primary concern regarding injury is initial stiffness which, when impaired, is proposed to be related to the "knee joint collapse (Horita et al., 1996)" that has been observed following repeated SSC work (Horita et al., 1996). Initial stiffness and therein the ability to resist impact forces appears to be differentially affected by SSC work, evident in decreasing muscle activity during pre-activation and eccentric phases of SSC work, but not during the concentric phase (Avela & Komi, 1998b). These findings suggest a selective decrement in muscle activity prior to ground contact and during the eccentric phase of SSC movements resulting in a decrease in vertical stiffness, and in landing alone, implicitly vertical impedance. As changes in isokinetic eccentric muscle strength have been observed following soccer-simulated exercise (M. Greig & Siegler, 2009), it seems likely that an impairment in pre-activation and eccentric muscle control accompanies soccer match duration. This has important ramifications regarding the ability to effectively control movement during high velocity actions that are integral to soccer, and a primary mechanism of injury in sport (Renstrom et al., 2008; Woods et al., 2004).

Table 3: Studies of SSC fatigue, and vertical and joint stiffness.

Researchers	-Fatigue Protocol	Stiffness Measure	Additional Measures	Primary Findings (pre- to post-exercise)
Horita et al. (Horita et al., 1996)	Sub-maximal drop jumps.	• Knee Joint stiffness.	• EMG of vastus lateralis • Blood lactate	• Significant decrease in knee joint stiffness at ground contact that was correlated with a decrease in drop jump performance. • Surface EMG of vastus lateralis during pre-activation phase of DJ increased significantly.
Horita et al. 1999 (Horita et al., 1999)	Sub-maximal drop jumps.	• Knee joint stiffness	• EMG of vastus lateralis • Blood Lactate	• Knee joint stiffness in push-off phase of drop jump decreased significantly. • Surface EMG of vastus lateralis during pre-activation phase of DJ increased significantly.
Dutto and Smith (Dutto & Smith, 2002)	Treadmill run to exhaustion at 80%VO_{2peak}	• Vertical stiffness • Leg stiffness	• Stride rate and length	• Decrease in vertical leg stiffness in fatigued running was the result of a greater center of mass displacement that was significantly related to changes in limb displacement.
Morin et al. (Morin et al., 2006)	4 x 100-meter sprints	• Vertical stiffness • Leg stiffness	• Sprint performance component	• Vertical leg stiffness during repeated 100-meter sprints was positively correlated with changes in mean and maximal sprint velocity.
Kuitunen et al. 2007 (Kuitunen et al., 2007)	Maximal & sub-maximal drop jumps.	• Leg stiffness	• EMG of vastus lateralis, medial gastrocnemius, soleus • Blood lactate	• No change in vertical leg stiffness during repeated maximal DJ's. • Sub-maximal DJ's led to a significant decrease in vertical leg stiffness that was significantly correlated with decreases in surface EMG of the soleus and gastrocnemius. • Decrease in vertical leg stiffness post-exercise was inversely correlated with increasing blood lactate.

General Lower Extremity Work and Coordinative Changes in Joint Range of Motion

Movement compensations resulting from strenuous exercise are thought to be the product of coordinative changes that allow for performance to be maintained (Orishimo & Kremenic, 2006a). Due to a paucity of analyses of joint range of motion in the soccer match simulation research, it is necessary to examine the effects of strenuous general lower extremity work on coordinative changes in the lower extremity (see Table 4). These studies allow for the generation of hypotheses regarding coordinative changes that may contribute to changes in lower extremity stiffness during the course of a soccer match and thereby increase in injury risk.

Foremost among these is the observation that strenuous general lower extremity exercise consistently results in an increased range of motion at one or more joints (Bonnard, Sirin, Oddsson, & Thorstensson, 1994; Borotikar, Newcomer, Koppes, & McLean, 2008; Chappell et al., 2005; Moran & Marshall, 2006a; Nyland, Caborn, Shapiro, & Johnson, 1999; Orishimo & Kremenic, 2006b; Rodacki, Fowler, & Bennett, 2002), with the knee reported to have the largest relative contribution to changes in sagittal plane range of motion (Bonnard et al., 1994; Chappell et al., 2005; Orishimo & Kremenic, 2006b). To a lesser extent hip flexion has been shown to increase with strenuous exercise (Borotikar et al., 2008; Orishimo & Kremenic, 2006a), while distally, ankle dorsiflexion has been documented to increase during prolonged exercise incorporating both hopping (Bonnard et al., 1994), and step-ups where it accounted for the smallest relative change in lower extremity joint range of motion (Orishimo & Kremenic, 2006a). The overall increase in sagittal plane range of motion across the three lower extremity joints may be characterized as a shared coordinative change that combine to decrease vertical stiffness, with the greatest contributor post-exercise being the knee joint, followed by the hip and finally ankle (Bonnard et al., 1994; Borotikar et al., 2008; Chappell et al., 2005; Orishimo & Kremenic, 2006a). Interestingly, kinematic changes in jumping and landing during soccer-simulated exercise have yet to be examined.

Table 4: Summary of findings regarding fatigue and movement.

Researchers	**Population**	**Fatigue Protocol**	**Movement examined**	**Primary Findings (pre- to post-fatigue)**
Orishimo et al.(Orishimo & Kremenic, 2006a)	Healthy males	Step-ups	Single-leg hop	• Increase in total range of motion at the knee. • Hip flexion angle decreased at heel strike, maximum total support moment, and final position leading to a more upright posture. • Increase in surface muscle EMG at the vastus medialis and vastus lateralis during pre-activation phase.
Chappell et al. (Chappell et al., 2005)	Healthy males and females	Sprinting and squat jumping	Stop jump	• Increase in anterior tibial shear force in landing, and increased knee flexion angle at peak anterior shear • In landing knee valgus increased in females, while knee varus increased in males. • Females had significantly less knee flexion at peak anterior shear force than males.
Moran and Marshall (Moran & Marshall, 2006b)	Physically active University males	Incremental treadmill running	Drop jump	• Increase in peak tibial acceleration occurred during the eccentric phase of 30cm DJ's. • Increase in peak angular velocity occurred during the eccentric phase of 30cm DJ's.
Bonnard et al. (Bonnard et al., 1994)	Active adult males	Two-footed hops	Two-footed hops	• Increase in knee flexion angle during landing phase of hopping. • Knee and ankle flexion decreased during the contact phase of hopping. • Surface EMG of the rectus femoris increased during the eccentric phase of hopping.
Borotikar et al. (Borotikar et al., 2008)	Female University athletes	Mixed squat and jump	Anticipated and unanticipated multi-planer jump landing and cutting	• During initial contact only hip ROM changed; showing a decrease in flexion and an increase in internal rotation. • During peak stance phase increases in peak knee abduction, knee internal rotation, and ankle supination occurred. • Fatigue related changes in movement were greater during un-anticipated trials compared to anticipated trials.

Validity and Development of the Individualized Soccer Match Simulation

The soccer match simulation developed for this study has been systematically designed to address the six previously defined fundamental short-comings in order to replicate the demands of a soccer match as closely as possible. The match simulation consists of seven different running intensities: 1) standing, 2) walking, 3) jogging, 4) low intensity running, 5) moderate intensity running, 6) high intensity running, and 7) sprinting (Mohr et al., 2003). The duration of time spent running at each intensity during the match simulation is designed to replicate that documented by Bangsbo et al. (Bangsbo et al., 1991) with subtle differences occurring at moderate and sprint intensities during the match simulation as documented in Table 5. The increased amount of moderate intensity running accounts for the lack of backwards running and shuffling that is observed in the match, while the greater amount of sprinting accounts for the lack of high-intensity actions involving a ball such as dribbling, and kicking.

The intermittent nature of a soccer match, with 1179 changes in activity pattern having a mean duration of 4.5-seconds (Bangsbo, 1994a, 1994b; Bangsbo et al., 1991) is closely replicated by the match simulation which includes over 1100 changes in locomotion activity with a mean duration of less than 6-seconds. The organization results in an acceleration and deceleration component being integrated with each fluctuation in intensity. The result is that the amount of SSC work performed during the match simulation more closely replicates that observed during an actual match. Additionally, the work performed during the testing intervals via sprinting and the integrated jump task is designed to replicate match performance. The match simulation's thirty sprints is within the range of 1 to 36 sprints documented (Bangsbo et al., 1991), while the thirty jumps performed in the match simulation is slightly greater than the 16 to 24 observed (Bangsbo, 1994b; Bangsbo et al., 1991). Due to the inability of the match simulation to include dynamic soccer-specific actions such as tackling the exchange in demand is speculatively equitable.

Table 5: Comparison of time spent across all intensities in match simulation versus match analysis.

	Percentage of time relative to 90-minute match duration.	
Intensity	Match simulation	Match Analysis (Bangsbo et al., 1991)
Standing	23.33%	14-22%
Walk	23.33%	38-45%
Jog	12.44%	14-18%
Low	21.78%	11-21%
Moderate	9.33%	5-6%
High	3.11%	2-3%
Sprint	~2.07%	0.6-0.8%

Prescription of Sub-Maximal Running Speeds and Total Distance Covered

The use of the YYIR1 to prescribe the sub-maximal running speeds in the match simulation stems from the observation that the YYIR1 test is significantly correlated to physical performance during a soccer match (Krustrup et al., 2003; Krustrup et al., 2005). Specifically, in males, YYIR1 performance is significantly correlated to the amount of high-intensity running (r=0.71), combined high-intensity running and sprinting (r=0.58), as well as total distance covered (r=0.53) during a match (Krustrup et al., 2003). While, in females, YYIR1 performance is significantly correlated to the amount of high-intensity running during the final 15-minutes of each half of play (Krustrup et al., 2005).

The sub-maximal running speeds during the match simulation are determined and expressed as a percentage of maximal distance run during the YYIR1 ($YYIR1_{max}$). Sub-maximal running speeds were developed via two separate studies reporting $YYIR1_{max}$ and physical match performance. The first was across tactical positions in males (Mohr et al., 2003), and the other across low and high performers in females (Krustrup et al., 2005). In both studies physical match analysis was performed using a spectrum of 7 intensities defined according to running speed (see Table 6, italicized text). Utilizing the previously discussed correlations between $YYIR1_{max}$ and physical match performance, sub-maximal running speeds were approximated as a percentage of distance covered during the YYIR1 (see Table 6, non-italicized text). Defining sub-maximal running speeds in this manner produced running speeds that closely replicate the match analyses running speeds (Table 7). Comparison of match analyses and the match simulation running speeds via a paired t-test (df=4) revealed no significant differences in the males, while in females a significant difference was observed in mean (p=.006) and low performers (p=.003), but not high performers. This significant difference is arguably the result of the match analysis defining the same sub-maximal running speeds in females (Krustrup et al., 2005) as were used for analyses in males (Bangsbo et al., 1991; Mohr et al., 2003). Interestingly, the researchers discuss adjusting their definition of sprint speed, lowering the speed from $30km \cdot h^{-1}$ to $25km \cdot h^{-1}$ (Krustrup et al., 2005) but making no further adjustments at the sub-maximal running speeds. It seems logical that an adjustment should have been made across all running speeds, and that this is the primary cause of the significant difference between the match simulation and the match analysis running speeds in females.

Table 6: Spectrum of match analyses running speeds relative to maximal YYIR1 running speed.

[All running speeds are expressed in $m \cdot s^{-1}$, and match simulation intensities expressed relative to maximal YYIR1 running speed.]

Running Intensity	***Running speed in match analyses*** (Krustrup et al., 2005; Mohr et al., 2003)	**Running speed (% of maximal YYIR1 running speed)**
Standing	----	**----**
Walking	***1.66***	**20-39%**
Jogging	***2.22***	**40-59%**
Low Intensity	***3.33***	**60-83%**
Moderate Intensity	***4.16***	**84-94%**
High Intensity	***4.99***	**105-109%**
Sprinting	***8.33(males) 6.90(females)***	**----**

The resulting total distance run during the match simulation compared to the match analyses (Table 8), is within the standard deviation observed across all positions except for defenders. This difference is speculatively the result of central defenders displaying a higher level of fitness than that which is required of them during a match, likely due to the tactical role which they play in the game. In females, where a range of performance was reported, the match simulation prescription consistently under-estimates the total distance run compared to the match analysis. Comparison of variability in physical performance between matches in males by position is documented to be between 5.2 and 8.9% (Di Salvo et al., 2007), the difference between the match simulation prescription and the actual match analyses from which it was derived ranges from 0.9 to 6.2%. This latter component is crucial as it demonstrates the validity of the match simulation to effectively simulate the physical demands of a soccer match as measured by total distance covered.

Table 7: Comparison of sub-maximal running speeds of match analysis with match simulation.

[All running speeds expressed in $m \cdot s^{-1}$. Match simulation running speeds are derived from findings of Mohr et al. (Mohr et al., 2003) and Krustrup et al. (Krustrup et al., 2005).]

Running intensity	**Match analysis** (Krustrup et al., 2005; Mohr et al., 2003)	**Match Simulation Running Speeds ($m \cdot s^{-1}$)**						
		Males				**Females**		
		Mid-fielders	Full-backs	Attackers	Defenders	Mean	Low	High
Walk Intensity	1.66	1.38	1.37	1.35	1.33	1.27	1.17	1.34
Jog Intensity	2.22	2.31	2.30	2.26	2.23	2.12	1.96	2.25
Low Intensity	3.33	3.34	3.33	3.26	3.23	3.07	2.83	3.25
Moderate Intensity	4.17	4.15	4.14	4.06	4.01	3.82	3.52	4.05
High Intensity	4.99	4.99	4.98	4.88	4.83	4.59	4.23	4.86

Table 8: Comparison of total distance run in match analysis versus match simulation by position.

[All distances expressed in kilometers. Match simulation distances calculated from the findings of Mohr et al. 2003 (Mohr et al., 2003) and Krustrup et al. 2005 (Krustrup et al., 2005)]

	Males [Match analysis distance via Mohr et al. (Mohr et al., 2003)]				**Females [Match analysis distance via Krustrup et al. (Krustrup et al., 2005)]**		
Total Distance Run	Mid-fielders	Full-backs	Attackers	Defenders	Mean	Low	High
Match Simulation	10.9	10.8	10.6	10.5	10.0	9.3	10.6
Match Analysis	11.0 ±0.21	10.98 ±0.23	10.48 ±0.22	9.74 ±0.22	10.5	9.7	11.3

Chapter Summary

The purpose of this literature review was to provide a basis for studying changes in movement and performance occurring during a soccer match simulation. The theoretical connection between soccer match duration and changes in movement mechanics that may contribute to the increasing injury rate documented to occur with soccer match duration has resulted in an area of research focused on the effect of soccer simulated exercise on movement mechanics and functional performance. While the physiological demands of a soccer game have been replicated via several match simulations, these protocols have not effectively accounted for several intrinsic components of soccer. Foremost is the need to account for the individual variability in fitness level among participants, the addition of SSC activities in the exercise protocol, and a progressive analysis of movement and performance deficits in a way that emulates the injury pattern documented in soccer.

Because it has been suggested that changes in movement mechanics are a likely contributor to the increase in injury with soccer match duration, it is essential that the intermittent nature of soccer, corresponding fluctuations and range of intensities, and the amount of SSC work accompanying the accelerative and decelerative components inherent in actual match play be addressed in a match simulation. Inclusion of these components, as well as the individualization of the soccer match simulation via a field test correlated to soccer match performance represent a significant progression of the previous research performed in this area. This dissertation examined progressive changes in movement mechanics during the course of an individualized soccer match simulation via measurement of vertical leg, and lower extremity joint stiffness and impedance during jumping and landing, respectively. A decrease in vertical stiffness characterizes a decreased ability of the musculature to control movement, resulting in a corollary increase in stress of the passive structures leading to an increase in injury risk (Dutto & Smith, 2002). In this manner this dissertation examined changes in movement mechanics that contributed to the increase in injury that is observed to occur with increasing duration of a soccer match.

CHAPTER III

RESEARCH DESIGN AND METHODS

The primary objective of this study was to examine progressive changes in movement mechanics and performance during an individualized soccer match simulation. The soccer match simulation consisted of 90-minutes of intermittent sub-maximal and maximal running that was structured in the same manner as a competitive soccer match in two 45-minute halves separated by a 15-minute half-time intermission. The soccer match simulation was individualized to the participants' soccer-specific fitness level 3-10 days prior via the yo-yo intermittent recovery test level 1 (YYIR1) (Krustrup et al., 2003), with performance on the YYIR1 dictating the five sub-maximal running intensities: 1) walking, 2) jogging, 3) low-intensity running, 4) moderate intensity running, and 5) high-intensity running incorporated in the match simulation. During the soccer match simulation testing of movement and performance were integrated into the demands of the match simulation, allowing for the periodic analysis of changes in movement mechanics and performance with match simulation progression. Specifically, vertical and lower extremity joint stiffness and impedance in jumping and landing, and performance during jumping (jump height), running (sprint speed) and cutting (cutting speed), were measured during each testing segment. The primary hypotheses examined were as follows: 1) Lower extremity vertical stiffness during landing and jumping would decrease with soccer match simulation duration. 2) Lower extremity vertical impedance during single-leg landing would decrease with match simulation duration. 3) Squat jump height would remain stable during the soccer match simulation. 4) Modified counter-movement jump height, cutting speed, and sprint speed would decrease, while RPE would increase during the soccer match simulation.

The rationale for this method of examination was that previous literature suggests that increases in injury during a soccer match are coincidental with decrements in movement mechanics and performance during the course of a soccer match simulation. The progressive analysis utilized here to characterize changes in movement and performance during a soccer match simulation allows for a more meaningful comparison to be made with previous research that documents an increase in injury with match duration. The goal of this research was to better understand changes in movement mechanics that may contribute to the increase in injury risk that is documented to occur during the course of a soccer match.

Subjects

Twelve females and twelve males between the ages of 18 to 25 years of age, with a minimum of 8 years playing experience, all currently playing competitively at either the USSF amateur or NCAA collegiate level participated in the study. All subjects were currently free from lower extremity injury, and had no history of lower extremity surgery. Only field players participated in the study, due to the substantial variation in the demands of the match for this position goalkeepers were excluded. Written consent was obtained from all subjects prior to beginning their initial testing session.

Instrumentation

During both testing sessions, heart rate (HR) was sampled continuously via the Biorharness® (Zephyr Technologies, Auckland, NZ) and subsequently downloaded to a computer for further analyses. The YYIR1 test was conducted using a digitized recording of the test. During the match simulation the six-second interval tempo was set by a web-based digital metronome (www.webmetronome.com). Reflective circular 3m scotchlite® markers (2.4 cm in diameter) were placed on both sides of the body and secured via Velcro® applied directly to the skin, or compression shorts to minimize marker movement. Two-dimensional sagittal plane kinematic data was collected during the integrated jump task using a digital video camera sampling at a rate of 60Hz. Kinetic data was collected in the vertical, sagittal, and frontal planes using a piezoelectric Kistler force plate (Kistler North America, Amherst, NY) at a sampling rate of 1000Hz and stored digitally. Kinematic and kinetic data was thereafter analyzed using datapac 2K2 lab application software (Version 3.13, Run Technologies, Mission Viejo, CA) and exported to excel for subsequent analyses and reduction. Sprint speed and agility performance was measured with infrared timing gates (Brower timing systems Salt Lake City, UT) in milliseconds (ms) and recorded by hand and digitally stored in excel at the time of testing. Sprint speed was recorded as the time to complete the 10-meter split during the 505 test. Cutting performance was recorded as the time to complete the 10-meter distance surrounding cutting during the 505 test. Jump performance was measured as jump height in centimeters and calculated via vGRF during the integrated jump task. Rating of perceived exertion (RPE) utilizing the Borg 6-20 scale (E. Borg & Kaijser, 2006; G.

Borg, Hassmen, & Lagerstrom, 1987) was recorded by hand and digitally stored in excel at the time of testing.

Procedures

This testing protocol consisted of two separate test sessions. The first session consisted of the soccer-specific fitness testing (YYIR1) that was used to prescribe the match simulation, and familiarization to sprint, cutting, and jumping tasks utilized in the second testing session. The second test session consisted of a 90-minute soccer match simulation structured in the same manner as a competitive match. Prior to both testing sessions the subjects were asked to prepare in the three days prior as if the sessions were an actual match; they were asked to maintain the same dietary, hydration, and exercise habits in the days preceding the testing sessions as they would prior to a competitive match. Specifically, they were asked to abstain from alcohol for the 72 hours prior to the testing sessions, and perform no moderate to high-intensity exercise during the 48 hours preceding the testing sessions. The procedures utilized for each testing session were as follows.

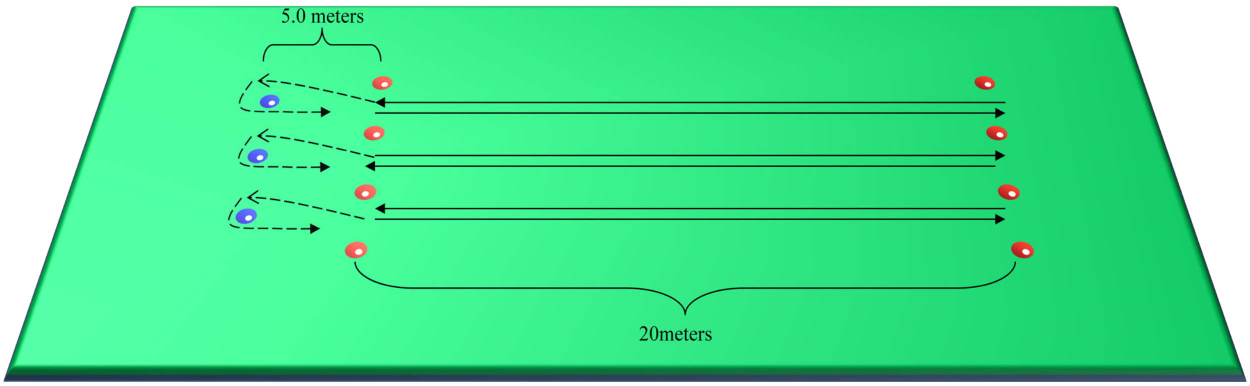
Test Session One

Following the subject's informed consent, their height, leg length, and weight were recorded. Thereafter, they were fitted with a heart rate strap that recorded HR continuously during the entire session. Prior to beginning testing and familiarization the subjects performed a progressive dynamic flexibility warm-up that was approximately 12-minutes in duration. The warm-up consisted of 3-minutes of jogging and low-intensity running followed by approximately 9-minutes of dynamic flexibility movements of increasing complexity and running at increasing intensities. The following was then performed in sequential order as described below.

Soccer-Specific Fitness Testing: Yo-Yo Intermittent Recovery Test

Soccer-specific fitness testing was conducted using a digitized recording of the YYIR1 test. The YYIR1 consists of 20-meter shuttle running with a 10-second active recovery interval comprised of 5-meters of walking (Figure 1) (Krustrup et al., 2003). The test is structured similar to a graded exercise test with fifteen stages, where running speed is increased steadily with each subsequent stage achieved and dictated via an audible beep. During the initial five stages running speed increases rapidly, and thereafter increased at a rate of 0.5 $km \cdot h^{-1}$. Following the initial five running stages, each subsequent stage is approximately 1-minute in duration and consists of eight shuttle runs. The subject continued to perform shuttle running until they were no longer able to maintain the pace dictated, or reached a state of volitional exhaustion. The final shuttle run completed by the subject was recorded as the total distance covered during the YYIR1. The maximal running speed on the YYIR1 was subsequently calculated as the average running speed during the final eight shuttle runs completed, and used to individualize all sub-maximal running speeds during the match simulation as previously discussed.

Figure 1: Yo-Yo intermittent recovery test (Krustrup et al., 2003).



Task Familiarization: Integrated Jump Task

After a recovery period of five to seven minutes following the completion of the YYIR1, the subject was familiarized to the integrated jump task that was used to examine changes in movement and performance during the match simulation. The integrated jump task was modified from Impellizzeri et al. (Impellizzeri, Rampinini, Maffiuletti, & Marcora, 2007) and consisted of three phases. The subject began standing with feet shoulders' width apart, one foot on the force plate and the other foot next to the force plate, and the arms placed across the chest. The subject began in a squat position with the knees bent to approximately 90 degrees, paused for approximately 3s. Phase one consisted of a squat jump (SJ), the subject jumping maximally upward on the "go" command given from the tester. Phase two consisted of a modified counter-movement jump ($_{m}$CMJ) where the subject absorbed the landing with both limbs (one landing in the center of the force plate and the other next to it) and immediately performing a second jump as high as possible. Phase three consisted of the subject landing on a single-limb and maintaining balance control on the force plate for approximately 2-seconds (see Figure 2). Between day reliability of the integrated jump task and analysis of the variables were examined previously and demonstrated strong intra-class correlation coefficient (ICC) values and low standard error of measurement (SEM) across all variables (Table 9).

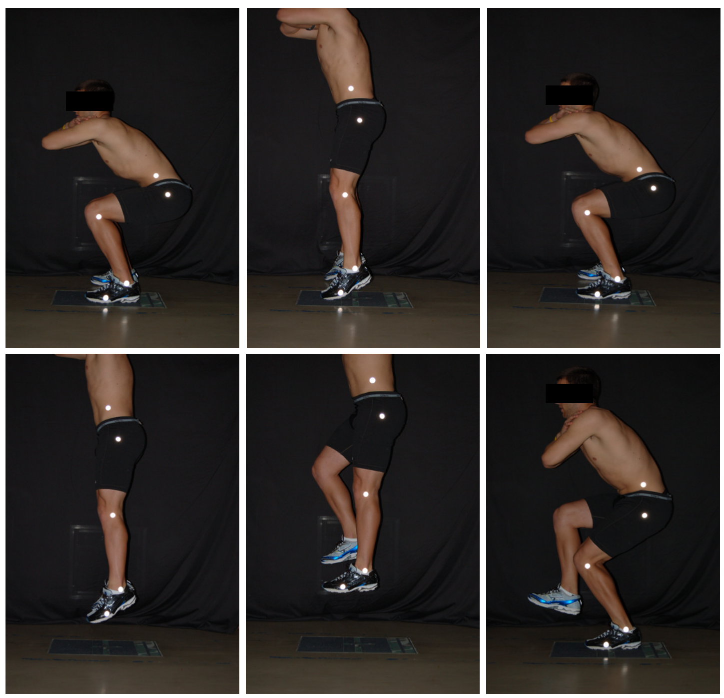
Table 9: Reliability analysis of the integrated jump task.

[Note: SEM is expressed in units of the measure. Thus, normalized vertical stiffness and vertical impedance are expressed in kilonewton·meters^{-1}·kg^{-1}, while SEM for SJ and mCMJ height are expressed in centimeters.]

VARIABLE	ICC (2,1)	SEM
Normalized Vertical Stiffness	0.94	0.014
Normalized Vertical Impedance	0.94	0.010
SJ Height	0.92	1.988
mCMJ Height	0.92	2.354

An acceptable trial was defined as one where the subject initiated the squat jump without a downward counter-movement (phase one), landed and jumped effectively so that only one foot contacted the center of the force plate (phase two), and landed in a single-leg balance position on the force plate (phase three). Familiarization to the jump task consisted of 12 successful trials on each limb. These trials were performed in random order between the dominant and non-dominant limb consistent with previous findings that random training resulted in greater task retention of complex movement skills over time than blocked practice (Memmert, 2006; Wright, Black, Immink, Brueckner, & Magnuson, 2004). Between each familiarization trial 45-seconds of passive recovery was provided in order to ensure maximal recovery.

Figure 2: Integrated jump task sequence.



Task Familiarization: 505 Agility Test

Next, the subject was familiarized to the 505 agility test which was used to measure performance decrements during the soccer match simulation. The 505 agility test consists of a 15-meter shuttle run, conducted around a single unilateral cutting movement (Draper & Lancaster, 1985; Gabbett, Kelly, & Sheppard, 2008). The testing set-up consisted of infrared light meters placed at a 1-meter height (Gabbett et al., 2008) and a distance of five and ten meters from the turning point. The subject began the run 0.5-meters behind the 15-meter line at their own volition following approval from the tester. Upon running through the first set of timing gates (15-meter) the timer for the entire task was triggered. As the subject passed through the second set of timing gates (5-meters) the lap time which measured the cutting speed was started. The subject then decelerated to cut off of a marked line (0-meters) using a pre-determined foot. Following the cutting action, participants ran back through the timing gates arranged at 5-meters, and 15-meters stopping both timers as they passed through (see Figure 3). The arrangement of the timing gates allowed for two performance parameters to be recorded: 1) sprint performance was recorded as the time required to complete the final 10-meters of the 505 test following the cutting task (see Figure 4), and 2) cutting performance which was recorded as the time to complete the cutting task between the start and stop timing gates set at 5-meters from the cutting point (see Figure 4). Familiarization to the task began with subjects running two sub-maximal runs cutting alternately on the right and left limbs. Thereafter, the subjects performed 7 alternating trials off of the dominant and non-dominant limbs with 60s recovery time between each trial. Cutting time was recorded for each trial. A minimum of 7 trials per limb was utilized as pilot testing previously indicated that this was the minimal number of familiarization trials required for stability in cutting time to be reached. If the time to perform the cutting task continued to decrease over the final three trials performed for the respective foot, familiarization continued until performance appeared stable.

Figure 3: 505 Test of horizontal agility (Draper & Lancaster, 1985; Gabbett et al., 2008).

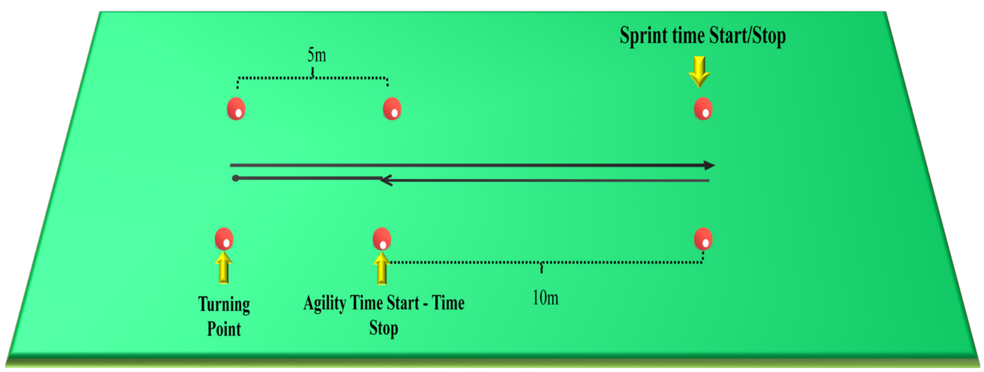
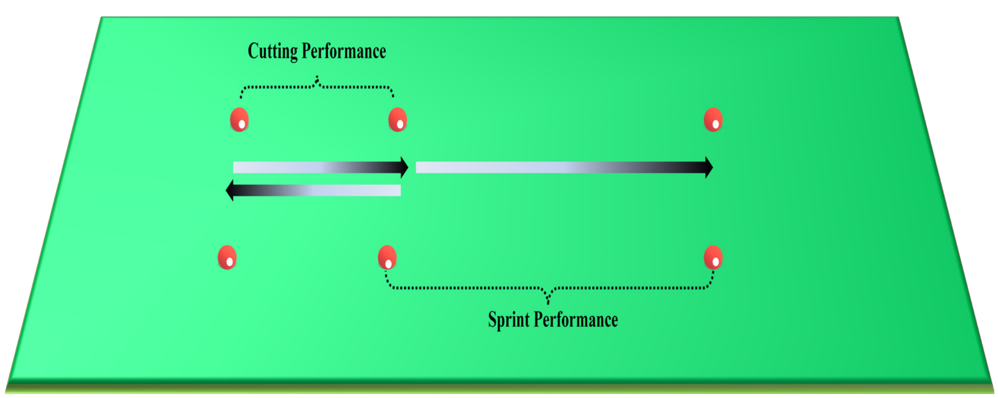


Figure 4: Performance measurements of cutting and sprinting during the 505 test.



Task Familiarization: Match Simulation

Following completion of familiarization to the 505 agility test, the subjects were familiarized to the sub-maximal running speeds which were prescribed via their performance on the YYIR1. Familiarization to running speeds consisted of the participant performing a minimum of four runs at each sub-maximal running speed. Once the participant was sufficiently comfortable with the variations in sub-maximal running speeds, they performed a single 7.5-minute segment of the match simulation protocol. This allowed for the participant to experience the sequencing of the match simulation protocol, the timing of sub-maximal running speeds, the integrated jump, and 505 agility testing.

Test Session Two

The second session was comprised of the 90-minute individualized soccer match simulation. Prior to beginning exercise the subjects were fitted with a pair of compression shorts and heart rate strap. Reflective markers were then placed on the right and left sides of the subject at the following bony landmarks of the lower extremity: 1) lateral superior portion of the iliac crest, 2) greater trochanter, 3) lateral joint line of the knee, 4) lateral maleollus, and 5) 5^{th} metatarsal. Following marker placement, all markers were circled with a permanent marker to allow for accurate replacement of marker(s) during testing. This allowed for markers to be replaced at any point during testing, and ensured that the marker was replaced with minimal error. The subjects then had the two testing tasks, integrated jump task and 505 agility test, demonstrated to them again and were asked if they had any questions regarding how to perform the tasks. The progressive dynamic flexibility warm-up then began. The initial 4-minutes of work consisted of jogging, low-intensity running, and walking at the subject's individualized speeds. Thereafter, the warm-up was progressed in a manner identical to that performed in test session one.

Task Familiarization and Pre-Testing

Following the warm-up the subjects performed a minimum of two sub-maximal trials of the integrated jump task and 505 agility test to ensure that they were well familiarized to the tasks. Subjects then performed four maximal trials of the integrated jump task and 505 agility test; these consisted of two trials on each limb for each test with 45 to 60 seconds recovery between each trial. Data from these trials were averaged and recorded as the subject's baseline values. All testing was counter-balanced between subjects for dominant and non-dominant limb, and 505 agility test and integrated vertical jump task as presented in Table 10.

Table 10: Counter-balance of testing segments.

Counter-Balance #1	Counter-Balance #2	Counter-Balance #3	Counter-Balance #4
Agility-Right	Agility-Left	CMJ-Left	CMJ-Right
CMJ-Left	CMJ-Right	Agility-Right	Agility-Left
Agility-Left	Agility-Right	CMJ-Right	CMJ-Left
CMJ-Right	CMJ-Left	Agility-Left	Agility-Right

Soccer Match Simulation: Structure and Organization

Following a 3 (minimum) to 5 (maximum) minute rest interval, subjects began the soccer match simulation. The soccer match simulation was structured in the same manner as a soccer match with two 45-minute halves and a 15-minute half-time intermission. Each 45-minute half consisted of six 7.5-minute segments of work that was comprised of two segments (Table 11). The first segment consisted of a 6-minute randomized intermittent exercise sequence consisting of forty paired 6-second bouts arranged into fifteen series of 24-seconds. The 24-second series was ordered as follows: 1) 6-seconds of sub-maximal running, 2) 6-seconds of walking and standing, 3) 6-seconds of sub-maximal running, and 4) 6-seconds of walking and standing (see Table 12).

Table 11: Arrangement of intermittent exercise and testing during match simulation.

	HALF ONE														**HALF TWO**											
Pre-Testing	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	**HALF-TIME**	***Post ½ Testing***	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*	Intermittent: 6-minutes	*Testing:1.5-minutes*

Table 12: Sample arrangement of a single randomized 6-minute intermittent exercise segment.

Bout	Work	Rest	Work	Rest
1	Low Intensity	Walk/Stand	Low Intensity	Walk/Stand
2	Jogging	Walk/Stand	Jogging	Walk/Stand
3	Low Intensity	Walk/Stand	Low Intensity	Walk/Stand
4	Moderate Intensity	Walk/Stand	Moderate Intensity	Walk/Stand
5	Low Intensity	Walk/Stand	Low Intensity	Walk/Stand
6	Jogging	Walk/Stand	Jogging	Walk/Stand
7	Low Intensity	Walk/Stand	Low Intensity	Walk/Stand
8	High Intensity	Walk/Stand	High Intensity	Walk/Stand
9	Low Intensity	Walk/Stand	Low Intensity	Walk/Stand
10	Jogging	Walk/Stand	Jogging	Walk/Stand
11	Moderate Intensity	Walk/Stand	Moderate Intensity	Walk/Stand
12	Low Intensity	Walk/Stand	Low Intensity	Walk/Stand
13	Low Intensity	Walk/Stand	Low Intensity	Walk/Stand
14	Jogging	Walk/Stand	Jogging	Walk/Stand
15	Moderate Intensity	Walk/Stand	Moderate Intensity	Walk/Stand

The 6-minute intermittent segments were arranged to allow for fluctuation in intensity to occur every 6-seconds resulting in a respective change from jog, low, moderate, or high running intensities to a subsequent 6-second bout of walking and standing, followed by a return sub-maximal run to the start position where a new series of runs ensues. Figure 4 illustrates the logistic arrangement that allowed for this movement to be accomplished. The second segment consisted of a 1.5-minute testing period integrating the sprint and jump components of the match simulation utilizing the previously described 505 agility test and the integrated jump task (Table 13). During the transition from intermittent running to testing and between testing modalities, the subject walked to the respective testing component, agility test or integrated jump task, and stood until testing occurs. With 15-seconds allotted for transition between the tests the subject spent any excess time standing. After completing the testing segment the subject transitioned back to the intermittent exercise segment via walking to the start point, where they were then prompted by the testers. Upon completion of each testing segment the participants were asked to rate their exertion level on the Borg 6-20 scale (E. Borg & Kaijser, 2006; G. Borg et al., 1987).

Figure 5: Logistical arrangement of the running for soccer match simulation.

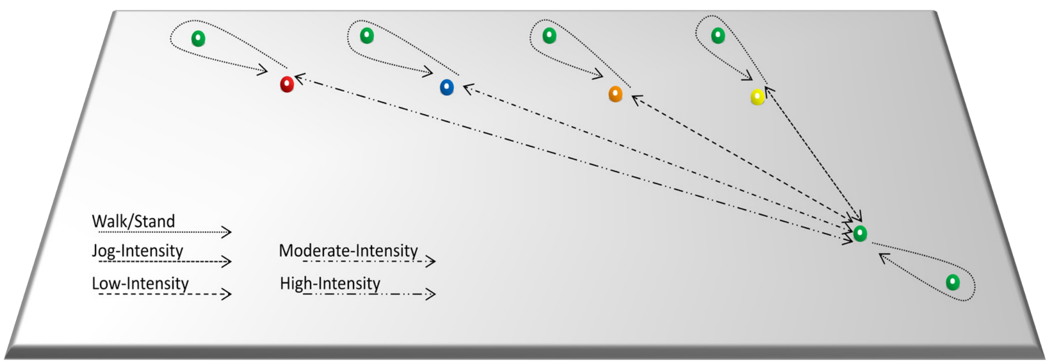


Table 13: Arrangement of a single 1.5-minute counter-balanced testing segment.

Testing Component	Estimated duration of action	Foot Tested
Walk/Stand	~15s	
505 Agility	~3s	Right
Walk/Stand	~15s	
Integrated Jump	~1s	Left
Walk/Stand	~15s	
505 Agility	~3s	Left
Walk/Stand	~15s	
Integrated Jump	~1s	Right
Walk/Stand	~15s	

During the 48 hours prior to both testing sessions, the subjects were asked to maintain habits consistent with their pre-match routine. Additionally, the subjects were asked to abstain from consuming any alcohol for the 72 hours prior to both testing sessions. During the half-time interval the subjects consumed eight to twelve ounces of a glucose-electrolyte solution (Gatorade®).

Data Processing

Demographic information consisting of age, height, weight, limb dominance, and years playing experience was collected prior to the start of test session one. During test session one the total distance covered during the YYIR1 test was recorded digitally on a computer. The following data was collected across the 14 time points of testing and recorded as follows. RPE, sprint, and cutting times were recorded by hand, and then immediately recorded digitally into an excel database. Two-dimensional kinematic and kinetic data collected during the integrated jump task was processed using Datapac 2K2 lab application software. Kinematic data was digitized using Datapac 2K2 software and a four-segment rigid body consisting of foot, shank, thigh, and pelvis segments was modeled from the five markers placed as previously described. Kinematic analysis of the integrated jump task trials was performed from 150ms prior to initiation of upward movement during phase one (squat jump) of the integrated jump through 150ms following phase three (single-leg landing). The kinematic data was collected at 60 Hz and filtered at 10Hz with a fourth order low pass butterworth filter at a 200ms time constant. The kinetic data was collected at 1000Hz and filtered at 60Hz with a fourth order low pass butterworth filter. Heart rate, kinetic, and kinematic data was subsequently exported to excel spreadsheets. During data reduction of kinetic and kinematic data, a lag between kinetic and kinematic data of 150ms (±1.1ms), that was noted during pilot testing was addressed by conducting a time shift of kinematic data in order to synchronize kinematic and kinetic data.

Data Reduction

Sprint, cutting performance, and RPE data were integrated into a single database following testing. Heart rate was analyzed in excel to determine peak HR during the YYIR1 test, while average and maximal heart rates during the first and second halves, and the entire match simulation were calculated. Utilizing R version 2.9.2 software the exported kinetic and kinematic data was processed as follows. The integrated jump task was divided into its constituent phases: 1) squat jump: 150ms prior to takeoff through 150ms after toe-off, 2) modified counter-movement jump: 100ms prior to touch-down through 100ms after toe-off, and 3) single-leg landing: 100ms prior to touch-down through 1s after touch-down. Thereafter, jump height was calculated for the SJ and $_{m}$CMJ segments of the integrated jump task via integration of velocity and time. Total jump impulse ($J_{impulse}$) from peak center of mass displacement through toe-off was calculated via the following equation, where body mass was equal to m, while final and initial velocity are equal to v_f and v_i, respectively.

$$J_{impulse} = m(v_f - v_i)$$

Both SJ and the $_{m}$CMJ vertical jump height ($height_{com}$) was then calculated via the following equation, where g= the constant of gravity which was equal to $9.81 m \cdot s^{-2}$.

$$height_{com} = v_f/2g$$

Vertical stiffness ($N \cdot m^{-1}$) was calculated during the $_{m}$CMJ phase and vertical impedance ($N \cdot m^{-1}$) calculated during the single-leg landing of the integrated jump task. Both stiffness and impedance were calculated as the maximal vGRF (N) relative to the vertical displacement of the body's center of mass (m). Vertical displacement of the body's center of mass in the $_{m}$CMJ and single-leg landing were calculated via integration of acceleration and velocity from vGRF data (Cavagna, 1975). Vertical stiffness was calculated from initial contact, defined as 10N of vertical force to maximal center of mass displacement during the counter movement jump (Hughes & Watkins, 2008). Vertical impedance was calculated from initial contact through maximal downward excursion during the single-leg landing (Kulas et al., 2006). The resulting equation was utilized for calculating both stiffness and impedance, where k_{vert} equals vertical stiffness, and k_{i_vert} equals vertical impedance, F=maximal vGRF, and ΔL= center of mass vertical displacement, with each expressed in $N \cdot m^{-1}$ (Arampatzis, Bruggemann, & Metzler, 1999; Kulas et al., 2006):

$$k_{vert} = \frac{F}{\Delta L} \qquad k_{i\_vert} = \frac{F}{\Delta L}$$

Following calculation of stiffness and impedance, both values were thereafter normalized via division by the subject's body mass (kg).

Data Analysis

The match simulation was arranged to allow for movement and performance data to be collected at 7.5-minute intervals for both the dominant and non-dominant limbs, resulting in 14 data points for each dependent measure. In order to test the hypotheses that movement and performance decreased more rapidly in the second half than the first half, and at a higher rate towards the end of each half, a univariate piece-wise quadratic growth model was utilized. This analysis was applied to the following dependent variables: 1) vertical stiffness (dominant and non-dominant limbs), 2) vertical impedance (dominant and non-dominant limbs), and 3) performance variables (RPE, sprint speed, cutting speed, SJ and $_{m}$CMJ height). Physiological stress during the match simulation was quantified via heart rate, with average and maximal heart rate during the first and second half compared via a paired t-test. The level of significance in all analyses was set at p=.05.

Statistical Model

The statistical model was developed using hierarchical linear modeling (HLM) software 6.08 (Scientific Software International, Lincolnwood, IL). Specifically, the piece-wise component of the model applied allowed for between half effects to be analyzed, while the quadratic component allowed for rate changes within each half to be analyzed. Both components were applied to the data via dummy coded variables (Table 14), specifically, the dummy coded variables applied allowed for the defined analyses. The piece-wise component, allowed for comparison between halves, and was the result of coding half one with a value of zero and half two with a value of one (Table 14, column

"D"). The quadratic component, allowed for analysis of the rate of change, and was the result of squaring the coding of testing intervals (Table 14, column "time") between each half (Table 14 column "Time_2"). The multiplication of time with the piece-wise component (Table 14, column "T*D") allowed for analysis of the change occurring during the second half of the match simulation. Finally, the squaring of the time component and subsequent multiplication by the piece-wise component (Table 14, column T_2*D) allowed for analysis of the rate of change during the second half of the match simulation.

Table 14: Data coding for piece-wise quadratic growth model analyses.

SUBJECT	Match Time	Interval	Time	Time_2	D	T*D	T_2*D
1.00	0.00	1.00	0.00	0.00	0.00	0	0.00
1.00	7.50	2.00	1.00	1.00	0.00	0	0.00
1.00	15.00	3.00	2.00	4.00	0.00	0	0.00
1.00	22.50	4.00	3.00	9.00	0.00	0	0.00
1.00	30.00	5.00	4.00	16.00	0.00	0	0.00
1.00	37.50	6.00	5.00	25.00	0.00	0	0.00
1.00	45.00	7.00	6.00	36.00	0.00	0	0.00
1.00	60.00	8.00	0.00	0.00	1.00	0	0.00
1.00	67.50	9.00	1.00	1.00	1.00	1	1.00
1.00	75.00	10.00	2.00	4.00	1.00	2	4.00
1.00	82.50	11.00	3.00	9.00	1.00	3	9.00
1.00	90.00	12.00	4.00	16.00	1.00	4	16.00
1.00	97.50	13.00	5.00	25.00	1.00	5	25.00
1.00	105.00	14.00	6.00	36.00	1.00	6	36.00

Two series of statistical models were applied to the data. Series one analyzed changes in stiffness and impedance during the match simulation, while series two analyzed changes in performance measures during the match simulation. Time related variables in both models were coded as follows: half one (*time*), half two (*time2*), piece-wise dummy coding for between half comparisons (*D*). The dependent variables examined in series one (Statistical Model 1) were coded as follows: dominant stiffness ($DStiffness_{ti}$), non-dominant stiffness ($NStiffness_{ti}$), dominant impedance, ($DImped_{ti}$) and non-dominant impedance ($NImped_{ti}$). The dependent variables examined in phase two (Statistical Model 2) were coded as follows: dominant limb cutting speed ($Dcut_{ti}$), non-dominant limb cutting speed ($Ncut_{ti}$), sprint speed ($Speed_{ti}$), squat jump height (SJ_{ti}), modified counter-movement jump height ($mCMJ_{ti}$), and RPE (RPE_{ti}).

Statistical Model 1: Initial statistical model for analysis of stiffness and impedance.

$$\mathrm{DStiffness_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

$$\mathrm{NStiffness_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

$$\mathrm{DImped_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

$$\mathrm{NImped_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

Statistical Model 2: Secondary statistical model for analysis of performance measures.

$$\mathrm{Dcut_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

$$\mathrm{Ncut_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

$$\mathrm{Speed_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

$$\mathrm{SJ_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

$$\mathrm{mCMJ_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

$$\mathrm{RPE_{ti}} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \mathrm{e_{ti}}$$

The statistical model was characterized by an intercept that was indicative of the initial value at the start of the first half (π_0). Thereafter, time-related change in both models and for each dependent variable were thus characterized as follows: 1) change at start of the 1st half (π_1), 2) rate of change during the 1st half (π_2), 3) difference at the start of the 1st half (π_3) compared to start of the 2nd half (π_0+π_3), 4) difference in rate of change at start of the 1st half compared to the start of the 2nd half (π_4), 5) difference in rate of change between the 1st and 2nd half (π_5) (Figure 6). Analyses of both series of models were conducted using fixed effects. Relative to hypotheses 1 and 2, the significant decrease that was expected to occur with match duration in vertical stiffness and impedance, respectively, was examined via π_2 and π_5. Hypothesis 3 and 4 were similarly examined via π_2 and π_5, testing the hypothesis that no significant change would be observed in SJ performance (hypothesis 3), and the hypothesis that a significant decrease in $_m$CMJ height, cutting speed, sprint speed, and a significant increase in rating of perceived exertion (hypothesis 4) would occur with match duration. Hypotheses 1a, 2a, and 4a, tested the rate of change during the 1st and 2nd halves, and the rate of change between the two halves, was characterized by π_2 (rate of change occurring in half one) and π_5 (difference in the rate of change between the 1st and 2nd half), respectively. The change and rate of change that was anticipated to occur with soccer match duration for a single dependent variable (modified counter-movement jump height) is presented in Figure 6. It was expected that the dependent variables: vertical stiffness, vertical impedance, running speed, and cutting speed would show similar decreases and rates of decrease with exercise duration. Inversely, RPE was hypothesized to increase with exercise duration (Figure 7), while no significant change with exercise duration was hypothesized for SJ performance (Figure 8).

Figure 6: Statistical analysis of time-related changes and hypothesized time-related change in vertical jump height.

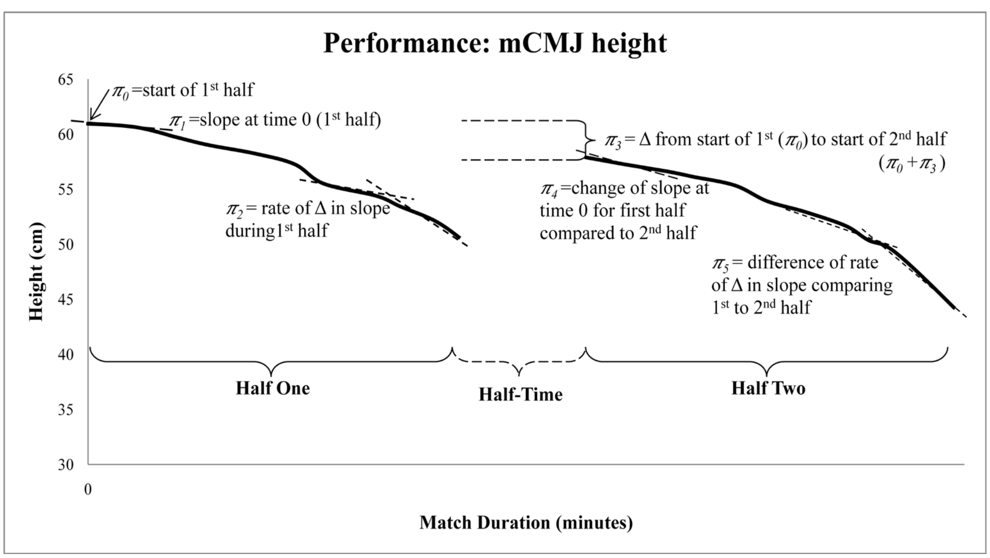


Figure 7: Hypothesized time-related change in RPE.

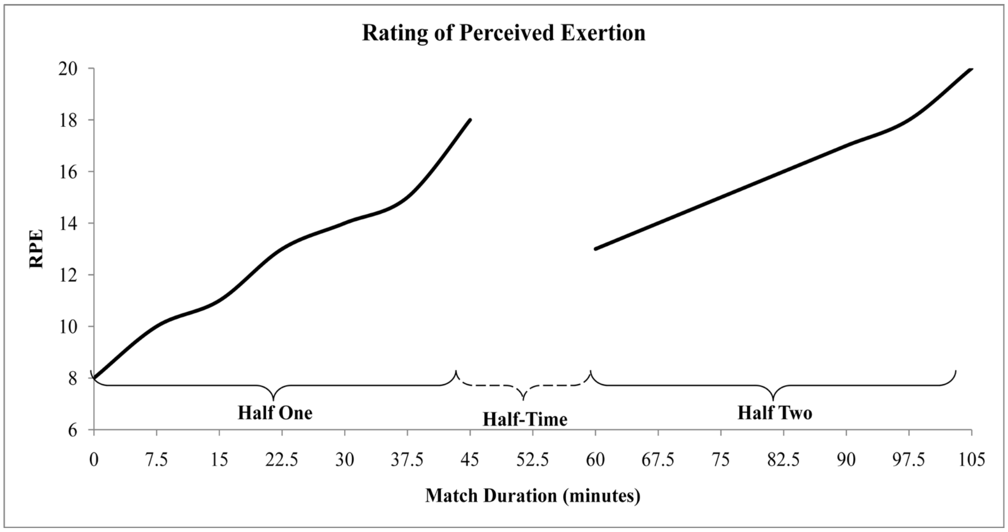
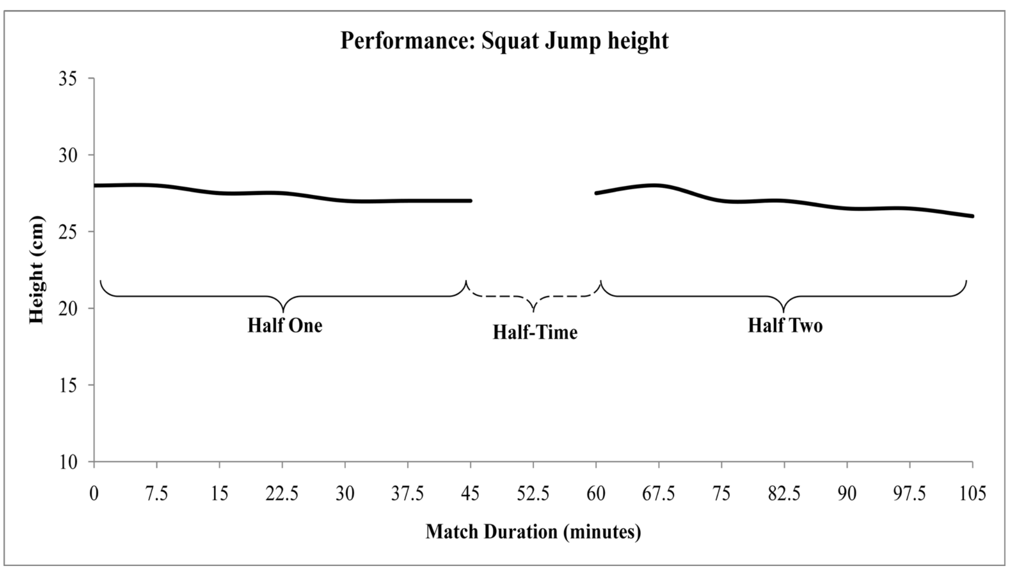


Figure 8: Hypothesized time-related change in SJ height.



Assumptions of normality and homogeneity were tested in SPSS (Chicago, IL). Specifically, assumptions of normality and homogeneity of the model residuals were examined via a normal Q-Q plot and histogram frequency distribution, respectively. Following confirmation that the aforementioned assumptions held, analysis was performed in HLM for each dependent variable as previously described.

CHAPTER IV

RESULTS

Twenty-four subjects (12 females and 12 males) participated and completed the two testing sessions required for the study. The mean age of all subjects was 19.5 ±1.38 years (females: 19.33 ±1.3, males: 19.66 ±1.50), mean height was 170.24 ±8.52 cm (females: 165.72 ±1.30, males: 174.76 ±8.05), and mean body mass was 66.47 ±6.47 Kg (females: 62.30 ±5.47, males: 70.64 ±4.44). The mean number of years playing experience in soccer for all subjects was 14.38 ±2.22 years (females: 13.75 ±2.22, males: 15 years ±2.13). All subjects were currently playing NCAA division one soccer, or within one year of completing their collegiate career at the same level and still playing competitively at the amateur level. All playing positions, except for goalkeepers, were represented by the subjects: forwards (4), defenders (6), and midfielders (14). The right limb was the dominant limb, defined as the preferred limb in kicking, in twenty-two of the twenty-four subjects, with the remaining two subject's left-foot dominant.

Physical and Physiological Demands of Testing

Testing was conducted at the same time of day between session one and session two for all subjects with the exception of one subject who was delayed by approximately two hours in arriving to the second testing session, thus beginning testing late in the evening (scheduled 7:00-10:00 p.m. versus actual 8:45-11:45 p.m.). Paired t-tests revealed no significant differences between session one and session two in mean temperature (23.70 ±0.24 °C vs 23.91 ±0.42°C, p=.142), mean humidity (57.66 ±4.3% v

59.50 ±4.77, *p*=.151), and barometric pressure (29.18 ±0.36 mmHg vs 29.24 ±0.10 mmHg, *p*=.400).

The mean performance on the YYIR1 test was 1,780 ±619.23 meters (females: 1,276.67 ±306.28, males: 2,283.33 ±393.94). This resulted in a mean match simulation distance of 10,165.52 ±1001.69 meters (females: 9,237.78 ±288.98, males: 11,093.26 ±369.52). Mean YYIR1 distance covered, corresponding maximal running speed, and resulting activity profile across all running intensities for the soccer match simulation is displayed in table 15.

Table 15: YYIR1 performance and associated mean prescribed running profile of soccer match simulation.

[Note: All distances are expressed in meters, and all speeds expressed in $m \cdot s^{-1}$. YYIR1 speed expresses the final running speed achieved.]

		MATCH SIMULATION						
	YYIR1	**Total**	**Walk**	**Jog**	**Low**	**Moderate**	**High**	**Sprint**
All (distance)	1780.00 ±619.23	10165.52 ±1001.69	1660.83 ±99.88	1486.4 ±89.52	3757.20 ±225.99	2004.23 ±120.67	803.15 ±48.35	903.75 ±13.45
All (speeds)	~4.48	-- --	1.32 ±0.08	2.21 ±0.13	3.19 ±0.19	3.98 ±0.24	4.78 ±0.29	-- --
Female (distance)	1276.67 ±306.28	9237.78 ±288.98	1579.83 ±49.34	1413.75 ±44.37	3573.92 ±111.79	1906.36 ±59.70	763.92 ±23.78	900.00 ±0.00
Female (speeds)	~4.25	-- --	1.25 ±0.04	2.11 ±0.07	3.04 ±0.10	3.78 ±0.12	4.55 ±0.14	-- --
Males (distance)	2283.33 ±393.94	10185.81 ±374.70	1741.83 ±64.11	1558.98 ±57.28	3940.48 ±144.92	2102.10 ±77.34	842.37 ±31.06	907.5 ±18.65
Male (speeds)	~4.69	-- --	1.38 ±0.05	2.32 ±0.08	3.35 ±0.12	4.17 ±0.15	5.01 ±0.18	-- --

The heart rate response to the YYIR1 from an exemplar subject is displayed in figure 9, with peak heart rate (HR_{peak}) during the YYIR1 defined as the maximal heart rate achieved during the test (refer to right axis of Figure 9). The heart rate during the match simulation was thus expressed in two manners (Figure 10), the first as beats per minute (bpm) [refer to left axis of figure 10], and second as percentage of HR_{peak} (refer to right axis of Figure 10). Due to hardware problems with the heart rate monitors YYIR1 testing data for 10 of the 12 females and 1 male subject was incomplete and thus is not reported. For the remaining subjects (N=13) HR_{peak} was 193.08 ± 8.13 beats per minute (bpm). The hardware problem persisted for 3 of the 12 females and 1 male subject during the match simulation. For this reason male subject data for the match simulation (N=11) is expressed both as a percentage of HR_{peak} (%HR_{peak}) and as bpm, while combined data for males and females (N= 19), and female data alone (N= 8) is expressed in bpm (Table 16).

Figure 9: Heart rate response to YYIR1 (exemplar data from a single subject).

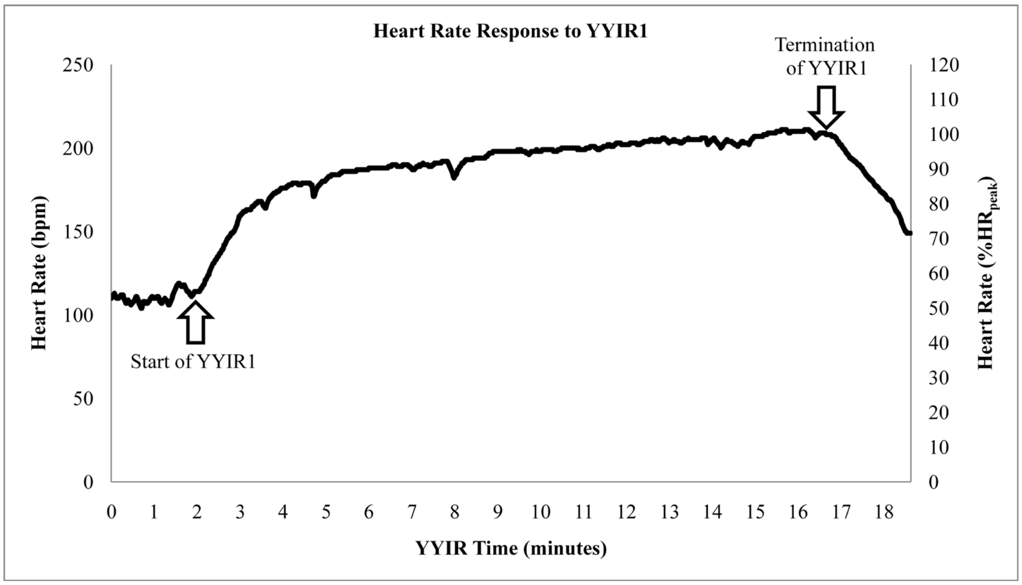


Figure 10: Heart rate response to individualized soccer match simulation (exemplar data from a single subject).

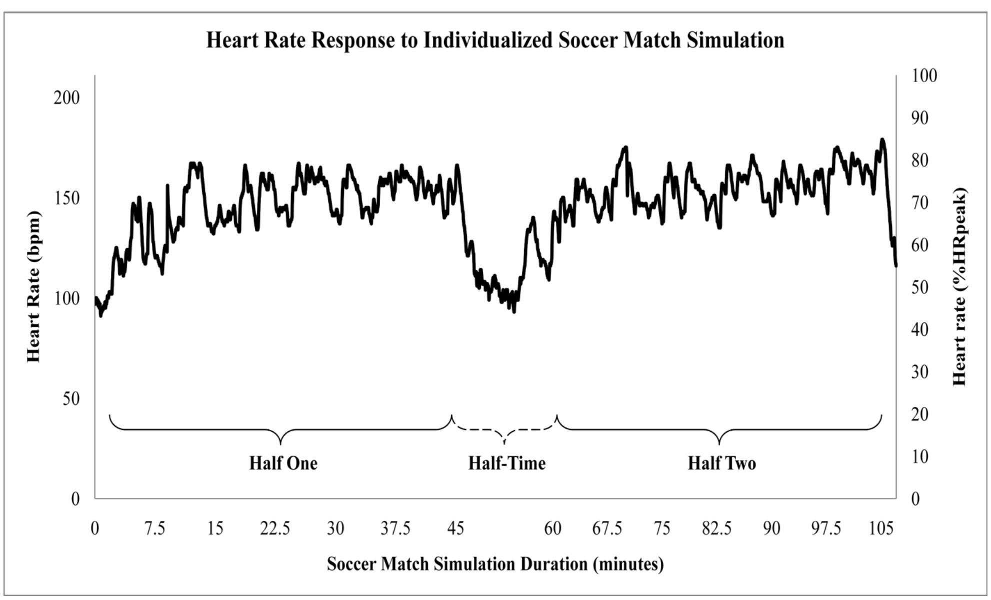


Table 16: Average and maximal heart rates during the soccer match simulation.

	Average HR (bpm)			Average HR (%HR_{peak})		
	Half One	**Half Two**	**Full**	**Half One**	**Half Two**	**Full**
Males (N=11)	150.27 (±11.63)	149.40 (±9.60)	150.49 (±10.06)	77.71% (±5.42)	76.56% (±4.04)	77.14% (±4.53)
Females (N=8)	156.13 (±14.68)	159.60 (±14.73)	158.13 (±14.68)	- -	- -	- -
All (N=19)	152.96 (±13.12)	153.93 (±12.86)	153.89 (±12.56)	- -	- -	- -
	Maximal HR (bpm)			**Maximal HR (%HR_{peak})**		
	Half One	**Half Two**	**Full**	**Half One**	**Half Two**	**Full**
Males (N=11)	182.00 (±18.53)	179.55 (±19.01)	188.18 (±22.62)	93.03% (±5.28)	89.70% (±3.72)	91.37% (±1.10)
Females (N=8)	193.50 (±20.14)	184.25 (±11.50)	193.75 (±20.00)	- -	- -	- -
All (N=19)	186.84 (±19.56)	181.53 (±16.06)	190.53 (±21.16)	- -	- -	- -

Match simulation heart rate, expressed relative to HR_{peak} (N=11) and thus for males only, revealed that subjects were working at a mean of 77.14 ±5.42% of their HR_{peak} (half one: 77.71% ±5.42 v half two: 76.56% ±4.04) with a maximal heart rate of 91.37 ±1.10% HR_{peak} (half one: 93.03% ±5.28 v half two: 89.70 ±3.72). Between half comparison of average revealed no significant differences average heart rate (152.96 ±13.12 vs 153.93 ±12.56 bpm, t=-0.69, p=.945) and peak heart rate (186.84 ±19.56 v 181.53 ±16.06 bpm, t=0.261, p=.798) via a paired t-test. Following completion of the soccer match simulation protocol, subjects were asked to subjectively compare how physically similar it was to an actual match on a scale from 0 to 10, with 10 being exactly like a match and 0 nothing like a match; the mean score for this subjective rating was 8.69 ±0.59.

Test of Assumptions of Normality and Homogeneity

To ensure that the statistical models utilized in this study did not violate assumptions of normality and homogeneity, the level-1 residuals for each dependent variable were analyzed separately in SPSS (Chicago, IL) with results displayed in Table 17. Normality was assessed by examining the degree to which the data deviated from being normally distributed, indicated by a value of zero. Homogeneity was assessed by examining the level of kurtosis observed in the data with values indicative of the distance the data moves from being mesokurtic. In addition to these analyses, subjective analyses via histogram and Q-Q plots of the residuals was also performed with these analyses presented in Appendix 1. These results revealed that homogeneity may be violated in two instances, RPE (skewness=-0.83, kurtosis=9.09) and dominant limb cutting (skewness=0.84, kurtosis=5.41). To account for the possible violation of normality and homogeneity, statistical analyses of these two variables was done using robust standard errors.

Table 17: Analysis of heterogeneity and normality

Variable	Dcut	Dimped	Dstiff	Ncut	Nimped	Nstiff	mCMJ	SJ	Sprint	RPE
Skewness	0.84	0.17	0.29	-0.11	0.88	0.46	-0.12	0.29	-0.09	-0.83
Kurtosis	5.41	1.531	0.109	0.62	2.51	0.84	0.59	0.11	-0.18	9.09

Progressive Change in RPE, Performance, and Movement Mechanics During the Individualized Soccer Match Simulation

Five time-related hypotheses were proposed and tested in order to analyze change in rating of perceived exertion (RPE), performance, and movement mechanics during the individualized soccer match simulation.

***Hypothesis 1*:** Rating of perceived exertion will increase with soccer match simulation duration.

- Hypothesis 1a: The increase in rating of perceived exertion would be greater in the second half than the first half, and there would be a faster rate of increase towards the end of each half of play.

Hypothesis 2: Sprinting and cutting speed, as well as modified counter movement jump height would decrease with soccer match simulation duration.

- Hypothesis 2a: The decrease in sprinting and cutting speed, and modified counter movement jump height would be greater in the second half than the first half, and there would be a faster rate of change towards the end of each half of play.

***Hypothesis 3*:** Squat jump height would remain stable during the soccer match simulation.

***Hypothesis 4*:** Lower extremity vertical stiffness during landing and jumping would decrease significantly with match simulation duration.

- Hypothesis 4a: The decrease in vertical stiffness would be greater in the second half than the first, and there would be a faster rate of decline towards the end of each half of play.

Hypothesis 5**:** Lower extremity vertical impedance during single-leg landing would decrease significantly with match simulation duration.

- Hypothesis 5a: The decrease in vertical impedance would be greater in the second half than the first, and there would be a faster rate of decline towards the end of each half of play.

The hypotheses were analyzed and are repeated consecutively for the following variables characterizing exertion and performance: 1) rating of perceived exertion, 2) sprint speed, 3) dominant and non-dominant limb cutting speed, 4) squat jump height, and 5) modified counter movement jump height. These analyses are then followed by results for movement mechanics of the integrated jump: 1) dominant and non-dominant limb vertical stiffness and 2) dominant and non-dominant limb vertical impedance.

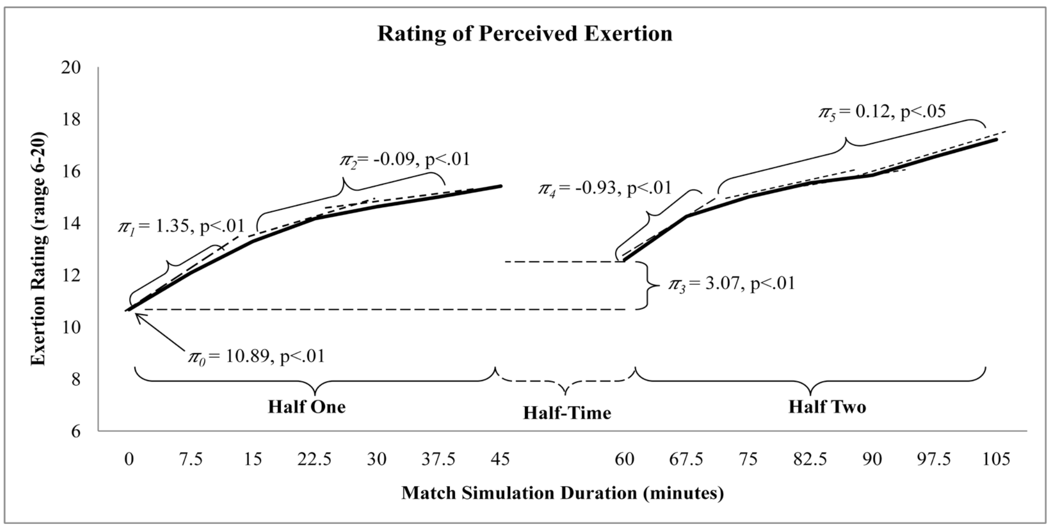
Analysis of Hypothesis 1: Rating of Perceived Exertion

Analysis of RPE revealed significant changes with increasing soccer match simulation duration (Figure 11). Subjects begin the match simulation reporting a mean RPE of 10.89 [(π_{0i}: coefficient *(Co-f)* =10.89), *p*=.00)], where statistical significance is indicative of the subjects' beginning the match simulation at a value different from zero. Thus, significance at π_{0i} is expected for all measures, and specifically for RPE, reflects the use of a scale ranging from 6-20. Analyses of the time-related change revealed that RPE was increasing [(π_{1i}(time): *Co-f* =1.35, *p*=.00)] 1.35 exertion units (EU) each 7.5-

minutes at the start of the first half and that this initial rate of increase slowed during the course of the first half [(π_{2i}(time2): *Co-f* =-0.09, *p*=.00)] at a rate of 0.10 EU's each 7.5 minutes**.** Between half comparisons revealed that the RPE at the start of the second half [(π_{3i}(D): *Co-f* =3.07, *p*=.00)] greater (13.96 EU's) compared to the start of the first half (10.89 EU's). Additionally, RPE at the start of the second half increased at a rate of 0.42 EU's, which was a slower rate [-0.93 EU's, (π_{4i}(D $*$ time): *Co-f* =-0.93, *p*=.008)] than that that observed at the start of the first half (1.35 EU's). In contrast, there was a slight increase in the rate of change in RPE with exercise duration during the second half equivalent to 0.03 EU's each 7.5-minutes [(π_{5i}(D $*$ time2): *Co-f* =0.12, *p*=.018)] compared to the first half where the rate of increase in RPE was slowing with exercise duration by 0.09 EU's each 7.5-minutes. Analysis of random effects, which characterized the variance component in the HLM model at the individual level, demonstrates that significant differences at the individual level persisted (p <.05 for all analyses) across all time-related analyses (Table 18).

It is important to note in the analysis of RPE that the change and rate of change observed were often correlated. These correlations suggest that the characteristics of the curve, or progressive changes, were related. Specifically, an inverse relationship is characterized by a low value at the preceding time point precipitating a larger increase, or higher rate of increase in RPE, respectively, in the ensuing analysis. The antithesis also holds true, a higher RPE, being accompanied by a smaller increase, or slower rate of increase, respectively. Specifically, RPE was characterized the following inverse relationships: 1) the change in RPE at the start of the first half (π_{1i}) and the rate of change in RPE during the first half (-0.914), 2) the initial RPE at the start of the second half (π_{3i}) and the change observed at the start of the half (π_{4i}) (-0.567), and 3) the change in RPE at the start of the second half (π_{4i}) and the rate of change occurring with second half duration (π_{5i}) (-0.98) (see appendix B1).

Figure 11: Statistical findings for rating of perceived exertion (RPE).



	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
RPEave	10.89	12.23	13.29	14.17	14.63	15.00	15.42		13.96	14.25	15.00	15.54	16.04	16.63	17.21
RPEsd	1.90	1.77	1.73	1.66	1.84	2.00	2.00		1.21	1.48	1.82	1.84	1.76	1.74	1.67

Table 18: Variance components for RPE with soccer match simulation duration.

Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	1.866	89.022	.000
TIME, slope R1	0.752	48.021	.002
TIME_2, slope R2	0.112	50.468	.001
D, slope R3	1.601	51.504	.001
TXD, slope R4	1.610	55.239	.000
T_2XD, slope R5	0.176	60.084	.000

Analysis of Hypothesis 2: Sprinting and Cutting Performance

Assessment of sprinting and cutting performance was performed via integrating each measure into the 505 agility test. Sprint performance was determined as the mean sprint speed in meters per second ($m \cdot s^{-1}$) of two 505 agility trials performed at each testing interval. Cutting performance was examined unilaterally in each trial for the dominant or non-dominant limb. Statistical analysis of mean sprint speed, as well as dominant and non-dominant limb cutting performance speed revealed significant time-related changes and between half differences among all variables (Table 19).

Table 19: Results of statistical analysis of changes in movement during the soccer match simulation.

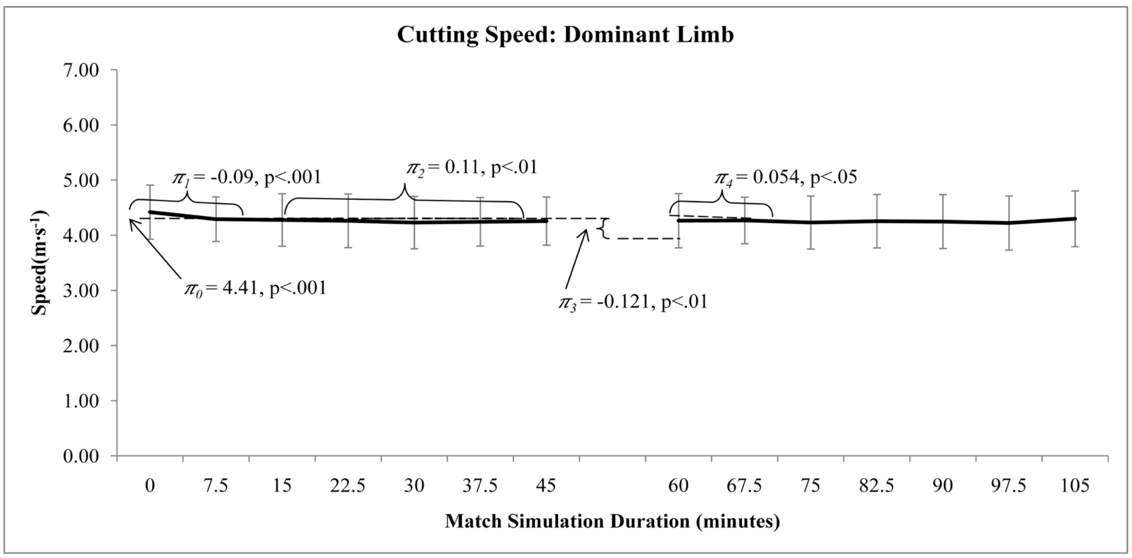
[Note: Cutting speed for the dominant and non-dominant limbs are represented as *Dcut* and *Ncut*, respectively. All values are expressed as: coefficeint, p-value]

Variable	π_{0i}	$\pi_{1i}(\text{time})$	$\pi_{2i}(\text{time2})$	$\pi_{3i}(\text{D})$	$\pi_{4i}(\text{D} * \text{time})$	$\pi_{5i}(\text{D} * \text{time2})$
Sprint	6.20, <.01	***-0.105, <.01***	***0.011, <.05***	***-0.278, <.01***	0.58, .14	-0.003, .61
Dcut	4.41, <.01	***-0.090, <.01***	***0.011, <.01***	***-0.121, <.01***	***0.054, <.05***	-0.005, .20
Ncut	4.34, <.01	***-0.059, <.01***	**0.006, <.05**	***-0.104, <.01***	0.017, .47	0.000, .85

Sprint Speed

Analysis of sprint speed revealed significant changes with increasing soccer match simulation duration (Figure 12, bold italics Table 19). Performance at the start of the match indicated that subject's mean initial sprint speed was 6.20 $m \cdot s^{-1}$ [(π_{0i}: *Co-f =6.20*), *p*<.01)]. Analyses of time-related change indicated that sprint speed was decreasing 0.105 $m \cdot s^{-1}$ each 7.5-minutes at the start of the first half [($\pi_{1i}(\text{time})$: *Co-f* = -0.105, *p*<.01)]. The rate of decrement in sprint performance slowed minimally during the first half at a rate of 0.011 $m \cdot s^{-1}$ each 7.5-minutes [($\pi_{2i}(\text{time2})$: *Co-f* =0.011, *p*<.05)]. Between half comparisons revealed that sprint speed at the start of the second half was .278 $m \cdot s^{-1}$ slower [$\pi_{3i}(\text{D})$: *Co-f* =0.278, *p*<.01)] relative to the start of the first half (half one: 6.20 v half two: 5.92 $m \cdot s^{-1}$). No significant between half differences in change, or the rate of change in sprint performance was observed. Analysis of the variance components of sprint speed in the HLM model utilized demonstrated that differences in the characteristics of the growth curve at the individual level were observed for all components, except the rate of change observed during the second half relative to the first (Table 20).

Figure 12: Changes in sprint performance with soccer match simulation duration.



	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
D_CUTave	4.42	4.29	4.28	4.26	4.23	4.24	4.26		4.26	4.27	4.23	4.25	4.25	4.22	4.30
D_CUTsd	0.31	0.31	0.31	0.32	0.28	0.33	0.28		0.33	0.32	0.30	0.33	0.33	0.35	0.34

Table 20: Variance components for sprint speed with soccer match simulation duration.

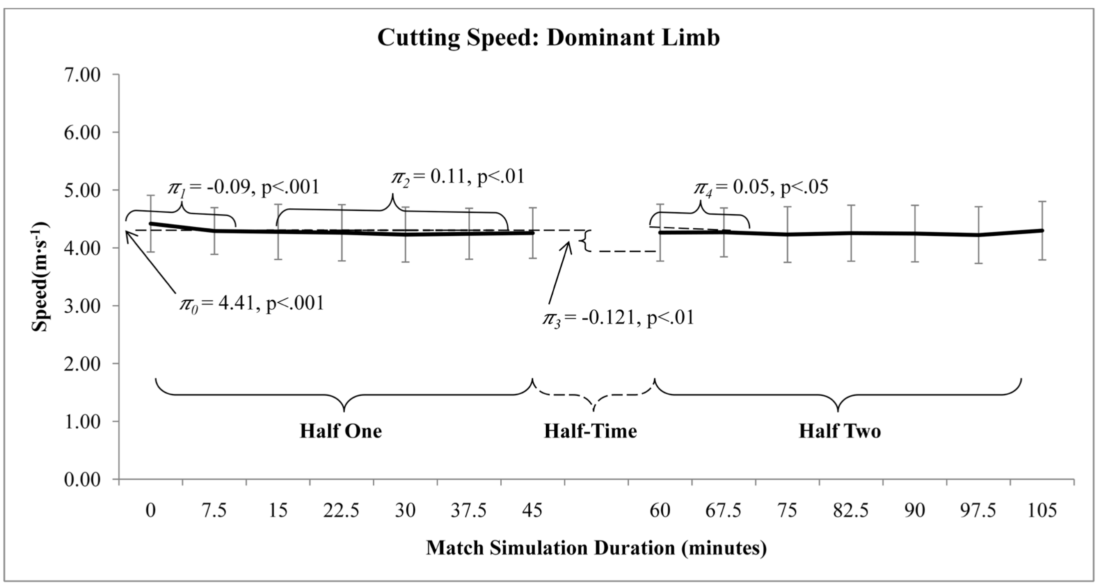
Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	0.441	323.339	.000
TIME, slope R1	0.101	47.679	.002
TIME_2, slope R2	0.015	43.412	.006
D, slope R3	0.190	50.478	.001
TXD, slope R4	0.122	38.142	.024
T_2XD, slope R5	0.018	34.341	.060

Cutting Speed

Analysis of cutting performance in both the dominant (Figure 13) and non-dominant (Figure 14) limbs revealed significant decrements with increasing exercise duration (bold italics Table 19). Performance at the start of the match simulation indicated that the mean cutting speed was 4.41 $m \cdot s^{-1}$ [(π_{0i}: *Co-f* =4.41), p<.01)]. Analysis of time-related change indicated that dominant limb cutting speed was decreasing 0.090 $m \cdot s^{-1}$ each 7.5-minutes at the start of the first half [$\pi_{1i}(\text{time})$: *Co-f* =0.090, p<.01]. The rate of decrease in dominant limb cutting speed slowed during the course of the first half at a rate of 0.011 $m \cdot s^{-1}$ each 7.5 minutes [$\pi_{2i}(\text{time2})$: *Co-f* =-0.011, p<.05]. Between half comparisons revealed that dominant limb cutting speed at the start of the second half was 0.121 $m \cdot s^{-1}$ slower than at the start of the first half (half one: 4.41 v half two: 4.29 $m \cdot s^{-1}$) [$\pi_{3i}(\text{D})$: *Co-f* = -0.121, p<.01]. Additionally, the performance at the start of the second half was changing 0.054 $m \cdot s^{-1}$ less each 7.5-minutes than at the start of the first half (half one: 0.090 v half two: 0.036 $m \cdot s^{-1}$) [$\pi_{4i}(\text{D} *$

time): *Co-f* =-0.054, p<.05]. No significant difference in the rate of change in dominant limb cutting was observed during the second half, indicating that the rate of change during half two was similar to that observed in the half one. Analysis of the variance components for dominant limb cutting speed in the HLM model utilized revealed no significant differences in the characteristics of the growth curve at the individual level (Table 21).

Figure 13: Changes in dominant limb cutting performance with soccer match simulation duration.



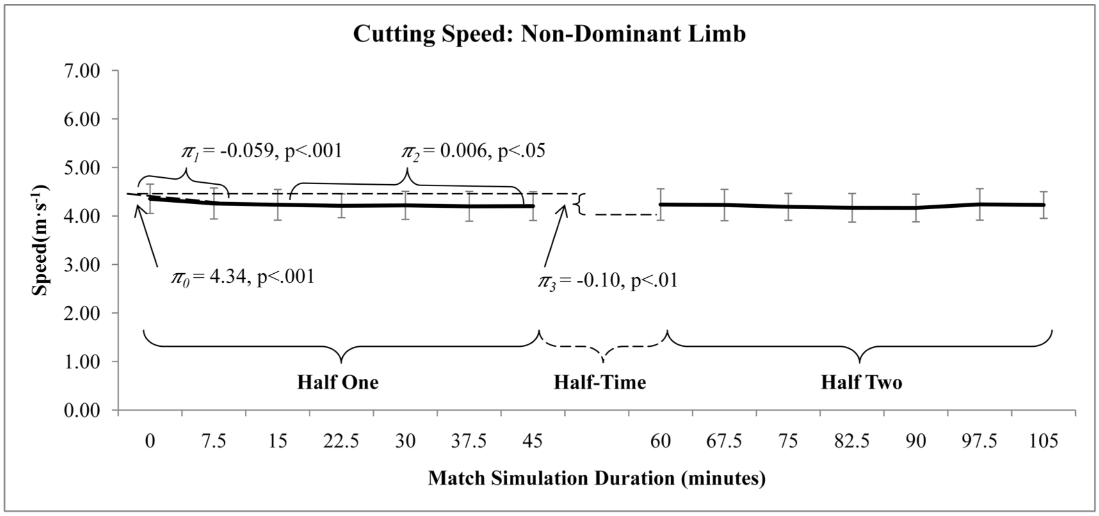
	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
D_CUTave	4.42	4.29	4.28	4.26	4.23	4.24	4.26		4.26	4.27	4.23	4.25	4.25	4.22	4.30
D_CUTsd	0.31	0.31	0.31	0.32	0.28	0.33	0.28		0.33	0.32	0.30	0.33	0.33	0.35	0.34

Table 21: Variance components for dominant limb cutting speed with soccer match simulation duration.

Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	0.091	267.125	.000
TIME, slope R1	0.002	25.787	.311
TIME_2, slope R2	0.000	28.510	.197
D, slope R3	0.008	27.676	.228
TXD, slope R4	0.004	21.932	>.500
T_2XD, slope R5	0.000	25.393	.330

Analysis of non-dominant limb cutting speed performance indicated that mean sprint speed was 4.34 $m \cdot s^{-1}$ [(π_{0i}: *Co-f* = 4.34, p<.01]. Analyses of time-related change indicated that performance was decreasing 0.059 $m \cdot s^{-1}$ each 7.5-minutes at the start of the first half [π_{1i}(time): *Co-f* = -0.059 p<.01]. No further changes in the rate of non-dominant limb cutting performance were observed during the first half. Between half comparisons revealed that non-dominant limb cutting performance at the start of the second half was 0.104 $m \cdot s^{-1}$ slower than at the start of the first half (half one: 4.34 v half two: 4.24 $m \cdot s^{-1}$) [π_{3i}(D): *Co-f* = -0.104, p<.01]. No further between half differences in non-dominant limb cutting speed were observed, indicating that the rate of change during half two was similar to that observed in the half one. Analysis of the variance components for non-dominant limb cutting speed in the HLM model utilized revealed no significant differences in the characteristics of the growth curve at the individual level (Table 22).

Figure 14: Changes in non-dominant limb cutting performance with soccer match simulation duration.



	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
N_CUTave	4.35	4.26	4.23	4.21	4.22	4.20	4.20		4.24	4.23	4.19	4.17	4.17	4.24	4.23
N_CUTsd	0.30	0.32	0.32	0.24	0.29	0.31	0.30		0.32	0.32	0.28	0.30	0.29	0.32	0.27

Table 22: Variance components for non-dominant limb cutting speed with soccer match simulation duration.

Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	0.091	269.269	.000
TIME, slope R1	0.001	23.939	.407
TIME_2, slope R2	0.000	31.430	.113
D, slope R3	0.002	25.004	.350
TXD, slope R4	0.002	25.787	.311
T_2XD, slope R5	0.000	32.745	.085

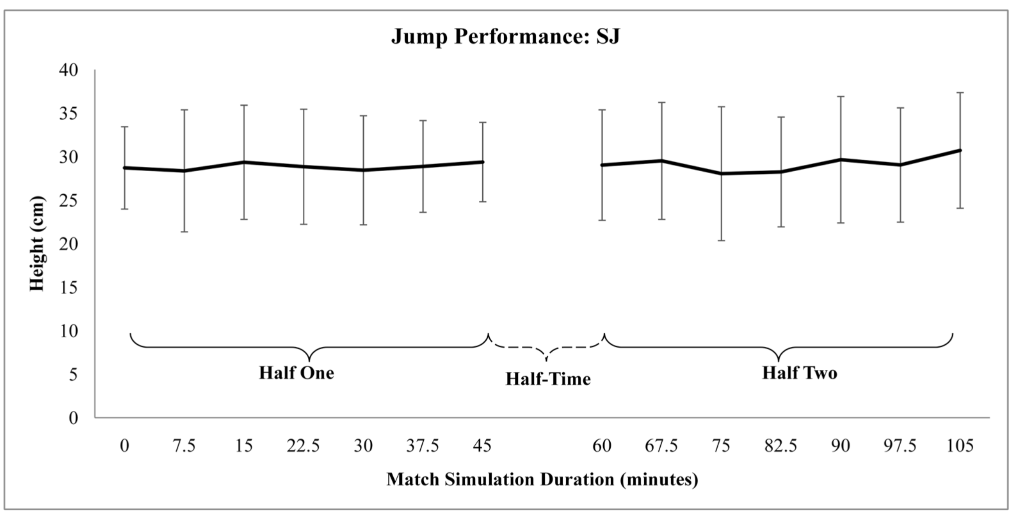
Analysis of Hypotheses 2 & 3: Squat Jump and Modified Counter Movement Jump Performance

Jump performance was examined via squat jump (SJ) height and modified counter movement jump ($_m$CMJ) height, both of which were components of the integrated jump task. The mean jump height of two trials at each testing interval was calculated for both $_m$CMJ and SJ. Findings indicate that subject performance varied at the start of the first half in both SJ [*Co-f* =28.55, *p*=.00] and $_m$CMJ [*Co-f* =27.33, *p*=.00]. Analysis of time-related changes with soccer match simulation duration in jump performance for SJ (Figure 15) and $_m$CMJ (Figure 16) revealed no significant change in either variable with exercise duration (statistical analyses Table 23). Subjective analysis indicated that both SJ and mCMJ height varied substantially during the match simulation, which may have contributed to the lack of significant time-related change. This observation was substantiated by calculation of the coefficient of variation (CV) for both SJ and mMCJ, which demonstrated a notably higher CV, ranging from 0.157 to 0.275 and 0.224 to 0.312, respectively, in contrast to that observed for RPE (0.096 to 0.178) where significant change was observed at all time points (Figure 17). The lowest CV calculated was observed in sprint (0.066 to 0.088) and cutting (dominant: 0.068 to 0.088, non-dominant: 0.067 to 0.088) performance which again appears substantially lower than that observed for SJ and $_m$CMJ height. Analysis of the variance components for SJ and $_m$CMJ height in the HLM model utilized revealed no significant differences at the individual level for SJ (Table 21). However, $_m$CMJ was characterized by individual level differences in the characteristics of the growth curve at the start of the first and second halves, as well as in the rate of change occurring during the first and second halves (Table 25).

Table 23: Results of statistical analysis of changes in movement during the soccer match simulation.

Variable	π_{0i}	$\pi_{1i}(\text{time})$	$\pi_{2i}(\text{time2})$	$\pi_{3i}(\text{D})$	$\pi_{4i}(\text{D} * \text{time})$	$\pi_{5i}(\text{D} * \text{time2})$
mCMJ	**27.33, .00**	0.544, .69	-0.053, .79	1.54, .62	0.484, .82	-0.031, .92
SJ	**28.55, .00**	0.211, .80	-0.014, .91	1.643, .39	-1.345, .31	0.215, .27

Figure 15: Changes in squat jump performance with soccer match simulation duration.

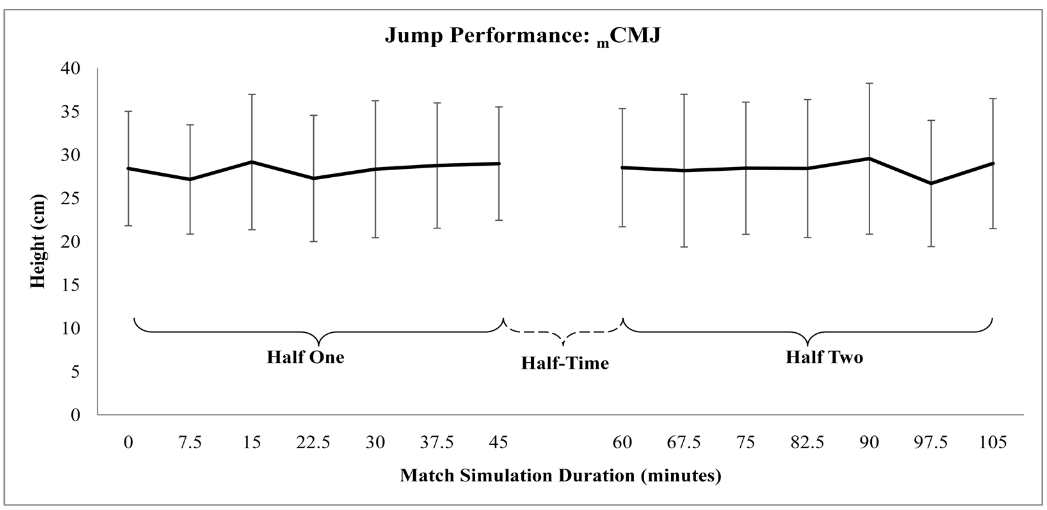


	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
SJave	28.7	28.4	29.4	28.8	28.4	28.9	29.4		29.0	29.5	28.0	28.2	29.7	29.0	30.7
SJsd	4.7	7.0	6.6	6.6	6.3	5.3	4.6		6.3	6.7	7.7	6.3	7.3	6.6	6.6

Table 24: Variance components for SJ performance with soccer match simulation duration.

Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	55.394	57.537	.000
TIME, slope R1	2.639	23.254	.446
TIME_2, slope R2	0.049	22.442	>.500
D, slope R3	18.448	22.913	>.500
TXD, slope R4	12.414	27.294	.243
T_2XD, slope R5	0.323	31.511	.111

Figure 16: Changes in modified counter-movement jump performance with soccer match simulation duration.

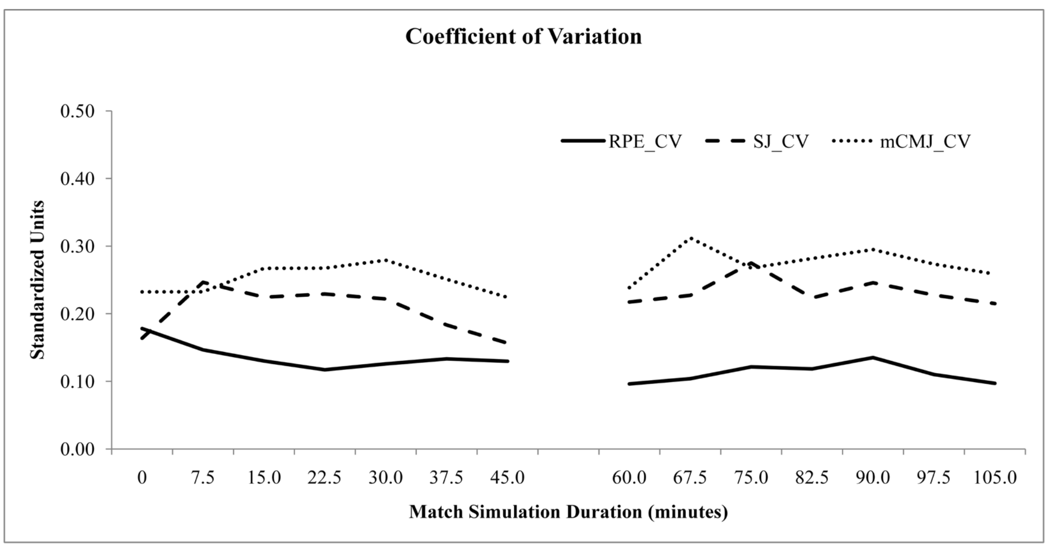


	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
mCMJave	28.4	27.1	29.2	27.3	28.3	28.7	29.0		28.5	28.2	28.4	28.4	29.5	26.7	29.0
mCMJsd	6.6	6.3	7.8	7.3	7.9	7.2	6.5		6.8	8.8	7.6	8.0	8.7	7.3	7.5

Table 25: Variance components for $_{m}$CMJ performance with soccer match simulation duration.

Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	42.018	30.164	.145
TIME, slope R1	16.555	36.493	.036
TIME_2, slope R2	0.401	41.567	.010
D, slope R3	98.465	32.005	.100
TXD, slope R4	54.598	38.551	.022
T_2XD, slope R5	1.187	43.686	.006

Figure 17: Comparison of coefficient of variation for integrated jump performance and RPE.



	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
RPEcv	0.18	0.15	0.13	0.12	0.13	0.13	0.13		0.10	0.10	0.12	0.12	0.14	0.11	0.10
SJcv	0.16	0.25	0.22	0.23	0.22	0.18	0.16		0.22	0.23	0.28	0.22	0.25	0.23	0.21
mCMJcv	0.23	0.23	0.27	0.27	0.28	0.25	0.22		0.24	0.31	0.27	0.28	0.29	0.27	0.26

Analysis of Hypotheses 4 &5: Vertical Stiffness and Vertical Impedance

Analysis of movement mechanics focused on two variables: lower extremity vertical stiffness and vertical impedance that was further divided into dominant and non-dominant limbs (Figures 18-21). Statistical results of movement data are displayed in Table 20. Vertical stiffness at the start of the match simulation was 0.052 and 0.056 kilonewton$\cdot$m$^{-1}\cdot$kg^{-1} for the dominant and non-dominant limb, respectively [dominant limb: *Co-f* = 0.052, *p*=.00, and non-dominant limb: *Co-f* = 0.056, *p*=.00]. Vertical impedance at the start of the match simulation was 0.232 and 0.242 kilonewton$\cdot$m$^{-1}\cdot$kg^{-1} for the dominant limb and non-dominant limb, respectively [dominant limb: *Co-f* = 0.232, *p*=.00, and non-dominant limb: *Co-f* = 0.242, *p*=.00]. Analysis of time-related changes during the first half demonstrated no significant changes in movement mechanics with exercise duration. Between half comparisons demonstrated no significant differences in movement mechanics from the first to the second half. Similar to the observations for jump height, subjectively, vertical stiffness and impedance in both limbs varied substantially during the match simulation, with this variability speculated to have contributed to the lack of significant time-related change. This observation was substantiated by subjective comparison of the CV for vertical stiffness (dominant: 0.236 to 0.418, non-dominant: 0.240 to 0.462) and impedance (dominant: 0.309 to 0.586, non-dominant: 0.361 to 0.543) demonstrating a notably higher CV, in contrast to that observed for RPE (0.096 to 0.178) where significant time-related change was observed across all time intervals. These differences in CV are graphically presented in figure 22 and 23, respectively, for vertical stiffness and impedance relative to RPE.

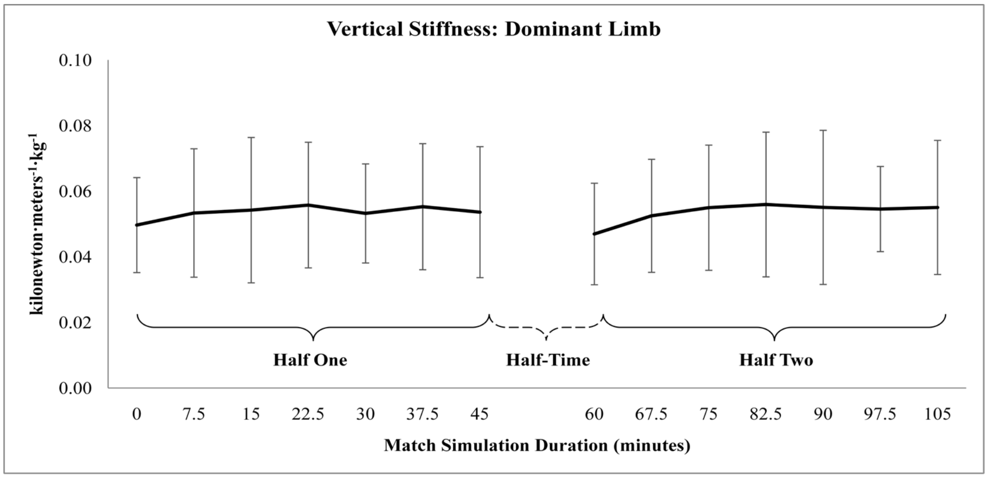
Analysis of variance components for vertical stiffness in the HLM model revealed no differences in the at the individual level for the non-dominant limb (Table 28), with the dominant limb, in contrast, being characterized by individual level differences in the change observed at the start of the second half, as well as the rate of change during the second half (Table 27). For vertical impedance, similar between limb differences were observed in analyzing the subject level variances via random effects (Table 29 and 30). These differences are characterized by dominant limb vertical impedance showing significant individual level differences in the characteristics of the growth curve; specifically, variability in the initial value at the start of half one and half two, and the change observed at the start of half two. For the non-dominant limb, these differences were characterized by subject level variability at the start of half two alone.

Table 26: Results of statistical analysis of changes in movement during the soccer match simulation.

[Note: Vertical stiffness for the dominant and non-dominant limbs are represented as *DStiffness* and *NStiffness*, while vertical impedance for the dominant and non-dominant limbs are represented as *DImped* and *NImped*. All values are expressed as: coefficeint, p-value.]

Variable	π_{0i}	$\pi_{1i}(\text{time})$	$\pi_{2i}(\text{time2})$	$\pi_{3i}(\text{D})$	$\pi_{4i}(\text{D} * \text{time})$	$\pi_{5i}(\text{D} * \text{time2})$
DStiffness	**0.052, .00**	0.002, .61	-0.000, .66	0.000, .95	0.000, .22	0.000, .91
NStiffness	**0.056, .00**	0.000, .95	-0.001, .84	-0.001, .88	0.002, .65	0.000, .74
DImped	**0.232, .00**	-0.002, .90	0.000, .90	-0.029, .36	0.025, .22	-0.003, .27
NImped	**0.242, .00**	0.009, .59	-0.001, .61	-0.020, .65	0.022, .43	-0.003, .42

Figure 18: Changes in dominant limb vertical stiffness with soccer match simulation duration.

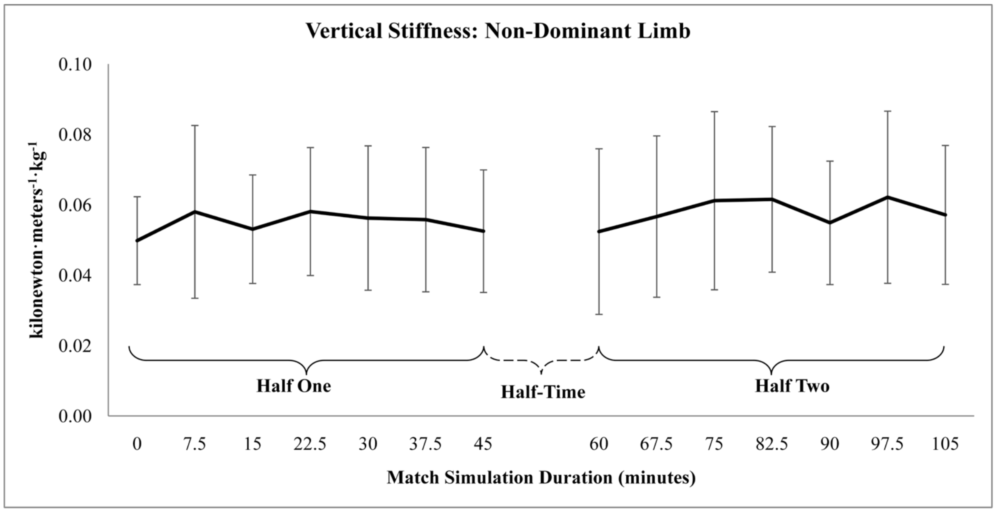


	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
D_STIFFave	0.050	0.053	0.054	0.056	0.053	0.055	0.054		0.047	0.053	0.055	0.056	0.055	0.055	0.055
D_STIFFsd	0.014	0.020	0.022	0.019	0.015	0.019	0.020		0.015	0.017	0.019	0.022	0.023	0.013	0.020

Table 27: Variance components for dominant limb vertical stiffness with soccer match simulation duration.

Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	14.769	55.192	.000
TIME, slope R1	0.205	19.199	>.500
TIME_2, slope R2	0.013	22.591	>.500
D, slope R3	5.693	21.058	>.500
TXD, slope R4	9.788	444.131	.005
T_2XD, slope R5	0.278	49.952	.001

Figure 19: Changes in non-dominant limb vertical stiffness with soccer match simulation duration.

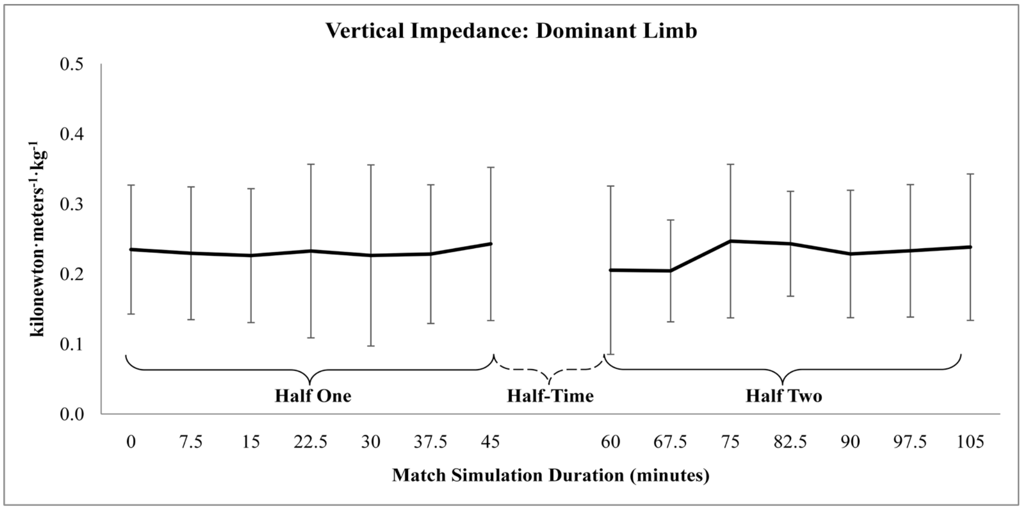


	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
N_STIFFave	0.050	0.058	0.053	0.058	0.056	0.056	0.053		0.052	0.057	0.061	0.062	0.055	0.062	0.057
N_STIFFsd	0.012	0.025	0.015	0.018	0.021	0.021	0.017		0.024	0.023	0.025	0.021	0.018	0.024	0.020

Table 28: Variance components for non-dominant limb vertical stiffness with soccer match simulation duration.

Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	20.178	57.423	.000
TIME, slope R1	1.217	22.704	>.500
TIME_2, slope R2	0.031	22.372	>.500
D, slope R3	8.232	28.698	.190
TXD, slope R4	8.495	32.545	.089
T_2XD, slope R5	0.204	30.224	.143

Figure 20: Changes in dominant limb vertical impedance with soccer match simulation duration.

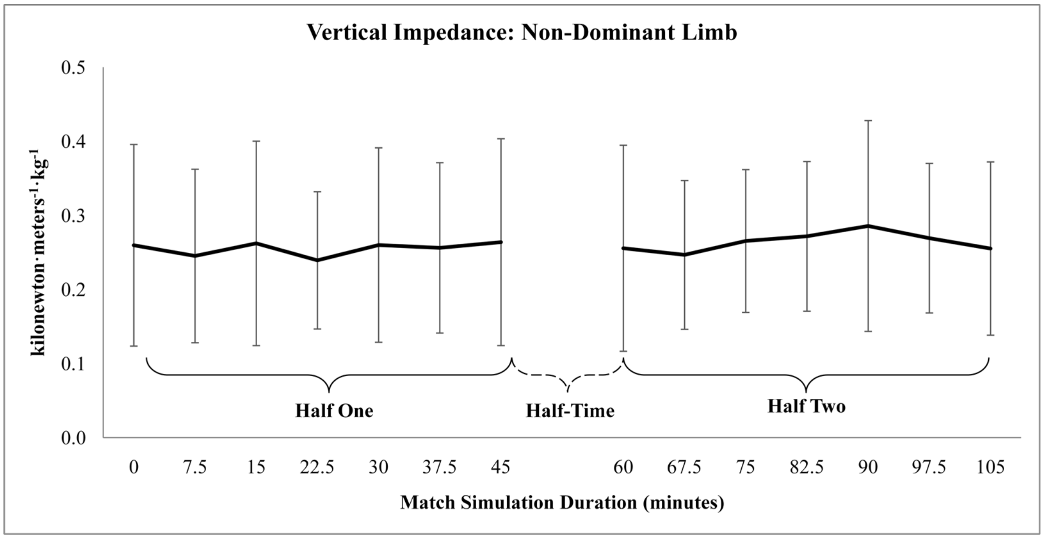


	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
D_IMPEDave	0.235	0.229	0.226	0.233	0.226	0.228	0.243		0.205	0.204	0.247	0.243	0.228	0.233	0.238
D_IMPEDsd	0.092	0.095	0.096	0.124	0.129	0.099	0.109		0.120	0.073	0.110	0.075	0.091	0.094	0.105

Table 29: Variance components for dominant limb vertical impedance with soccer match simulation duration.

Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	100.372	188.875	.000
TIME, slope R1	3.484	28.107	.211
TIME_2, slope R2	0.040	18.580	>.500
D, slope R3	21.616	45.008	.004
TXD, slope R4	12.121	41.816	.010
T_2XD, slope R5	0.260	34.679	.056

Figure 21: Changes in non-dominant limb vertical impedance with soccer match simulation duration.

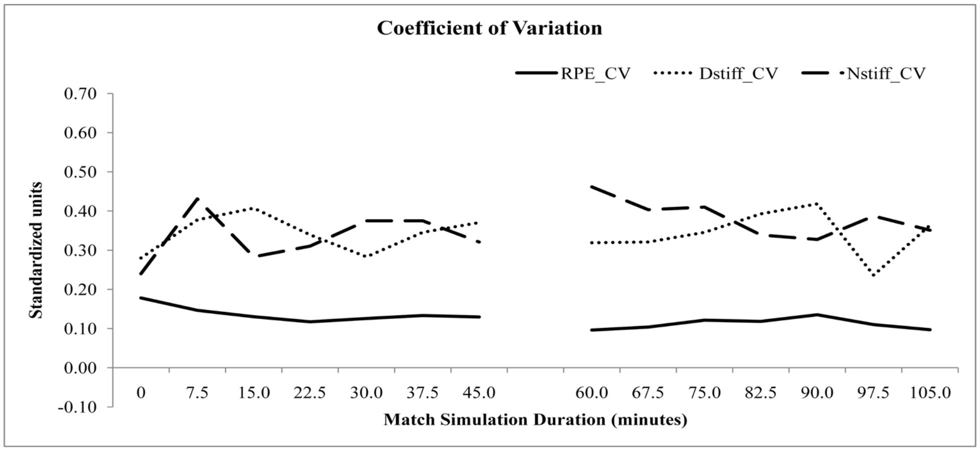


	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
N_IMPEDave	0.260	0.245	0.262	0.239	0.260	0.256	0.264		0.256	0.247	0.266	0.272	0.286	0.269	0.255
N_IMPEDsd	0.136	0.117	0.138	0.093	0.131	0.115	0.140		0.139	0.100	0.096	0.101	0.142	0.101	0.117

Table 30: Variance components for non-dominant limb vertical impedance with soccer match simulation duration.

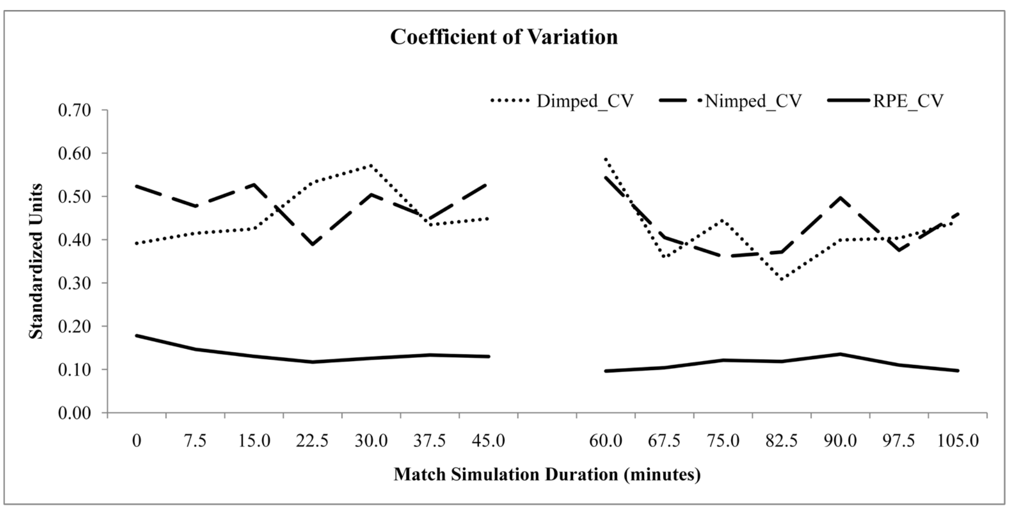
Random Effect	Variance Component	Chi-Square	P-value
INTRCPT1, R0	106.539	182.807	.000
TIME, slope R1	2.443	29.308	.170
TIME_2, slope R2	0.078	31.299	.116
D, slope R3	19.379	48.108	.002
TXD, slope R4	6.306	44.947	.052
T_2XD, slope R5	0.158	29.530	.163

Figure 22: Comparison of coefficient of variation for vertical stiffness and RPE.



	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
RPEcv	0.18	0.15	0.13	0.12	0.13	0.13	0.13		0.10	0.10	0.12	0.12	0.14	0.11	0.10
DSTIFFcv	0.28	0.38	0.41	0.34	0.28	0.35	0.37		0.32	0.32	0.35	0.39	0.42	0.24	0.36
NSTIFFcv	0.24	0.43	0.28	0.31	0.38	0.38	0.32		0.46	0.40	0.41	0.34	0.33	0.39	0.35

Figure 23: Comparison of coefficient of variation for vertical impedance and RPE.



	Half One								Half Two						
	0	7.5	15	22.5	30	37.5	45		60	67.5	75	82.5	90	97.5	105
RPEcv	0.18	0.15	0.13	0.12	0.13	0.13	0.13		0.10	0.10	0.12	0.12	0.14	0.11	0.10
DIMPEDcv	0.39	0.41	0.42	0.53	0.57	0.43	0.45		0.59	0.36	0.45	0.31	0.40	0.40	0.44
NIMPEDcv	0.52	0.48	0.53	0.39	0.50	0.45	0.53		0.54	0.40	0.36	0.37	0.50	0.38	0.46

Additional Exploratory Analyses

Subjective observations that performance variability during the integrated jump task may have masked potential changes in movement mechanics with exercise duration lead to three exploratory analyses. First, the potential contribution of running intensity during the intermittent running segments prior to the testing intervals to variability in movement mechanics and jump performance was examined. The rationale for this analysis was based on previous findings that intermittent high-intensity exercise during a soccer match resulted in transient decreases in performance (Bangsbo et al., 2006; Mohr et al., 2003). Second, vertical stiffness and vertical impedance in both the dominant and non-dominant limb were re-analyzed accounting for landing height of the preceding movement. This analysis was based on observations that increasing drop jump height resulted in decreasing vertical stiffness (Arampatzis, Bruggemann, & Klapsing, 2001), and findings during reliability testing of the integrated jump. Foremost that normalization of vertical stiffness to squat jump height in meters, resulted in a higher ICC value, increasing from 0.94 when normalized to the subjects body weight alone, to 1.00 when normalized to SJ height in addition to body weight with a SEM of 0.064 kilonewton$\cdot$meters$^{-2}\cdot$kg^{-1}. While this finding was exclusive to vertical stiffness (i.e. vertical impedance ICC remaining unchanged at 0.94 regardless of its additional normalization to $_{m}$CMJ height), additional analysis of vertical impedance was also performed. Third, subjective assessment of the contributors to vertical stiffness and impedance: peak vGRF and COM displacement were analyzed graphically. This final assessment allows for speculation regarding how stiffness and impedance may have been effectively maintained with increasing exercise duration by modulating lower extremity function.

Accounting for Running Intensity in Intermittent Segments Preceding Testing

Due to randomization of the running sequence within each half, running intensities varied prior to each testing interval. In order to examine if fluctuation in running intensity accounted for some of the variability in movement mechanics and jump performance during the soccer match simulation, running intensity was examined as a level-1 covariate with fixed effects. The running intensity during five different time intervals (i.e. 24, 48, 72, 96, and 120s) immediately preceding each testing interval (Table 21) were examined. Initial analysis was performed by adding the running intensity of all five time intervals as level-1 covariates to the previous univariate statistical models for vertical stiffness, vertical impedance, SJ, and $_{m}$CMJ (Statistical Model 3). Following this initial analysis non-significant time intervals were eliminated and significant time intervals retained in the model. Statistical analyses continued in this manner until the significant intermittent time intervals were examined individually.

Table 31: Mean distances run during the intermittent segments prior to testing intervals.

[All running distances are in meters and expressed as mean (±sd).]

Time prior to Testing Interval	**Match Simulation Time Interval (minutes)** (expressed: Half One/Half Two)					
	7.5/67.5	**15/75**	**22.5/82.5**	**30/90**	**37.5/97.5**	**45/105**
1 segment: 24s	63.54 (±3.83)	54.15 (±3.27)	54.15 (±3.27)	54.15 (±3.27)	63.54 (±3.83)	54.15 (±3.27)
2 segments: 48s	117.69 (±7.10)	108.29 (±6.54)	108.29 (±6.54)	108.29 (±6.54)	117.69 (±7.10)	108.29 (±6.54)
3 segments: 72s	171.83 (±10.37)	162.44 (±9.81)	162.44 (±9.81)	150.66 (±9.09)	181.22 (±10.93)	171.83 (±10.37)
4 segments: 96s	214.20 (±12.92)	216.59 (±13.08)	204.81 (±12.36)	204.81 (±12.36)	223.59 (±13.48)	214.20 (±12.92)
5 segments: 120s	213.89 (±98.88)	215.90 (±99.81)	233.46 (±60.50)	233.46 (±60.50)	264.97 (±75.00)	241.28 (±64.10)

Statistical Model 3: Exploratory analysis of sub-maximal running intensities in integrated jump.

$$\mathrm{DStiffness}_{ti} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \pi_{6i}24\mathrm{s} + \pi_{7i}48\mathrm{s} + \pi_{8i}72\mathrm{s} + \pi_{9i}96\mathrm{s} + \pi_{10i}120\mathrm{s} + e_{ti}$$

$$\mathrm{NStiffness}_{ti} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \pi_{6i}24\mathrm{s} + \pi_{7i}48\mathrm{s} + \pi_{8i}72\mathrm{s} + \pi_{9i}96\mathrm{s} + \pi_{10i}120\mathrm{s} + e_{ti}$$

$$\mathrm{Dimped}_{ti} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \pi_{6i}24\mathrm{s} + \pi_{7i}48\mathrm{s} + \pi_{8i}72\mathrm{s} + \pi_{9i}96\mathrm{s} + \pi_{10i}120\mathrm{s} + e_{ti}$$

$$\mathrm{Nimped}_{ti} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \pi_{6i}24\mathrm{s} + \pi_{7i}48\mathrm{s} + \pi_{8i}72\mathrm{s} + \pi_{9i}96\mathrm{s} + \pi_{10i}120\mathrm{s} + e_{ti}$$

$$\mathrm{mCMJ}_{ti} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \pi_{6i}24\mathrm{s} + \pi_{7i}48\mathrm{s} + \pi_{8i}72\mathrm{s} + \pi_{9i}96\mathrm{s} + \pi_{10i}120\mathrm{s} + e_{ti}$$

$$\mathrm{SJ}_{ti} = \pi_{0i} + \pi_{1i}(\mathrm{time}) + \pi_{2i}(\mathrm{time2}) + \pi_{3i}(\mathrm{D}) + \pi_{4i}(\mathrm{D} * \mathrm{time}) + \pi_{5i}(\mathrm{D} * \mathrm{time2}) + \pi_{6i}24\mathrm{s} + \pi_{7i}48\mathrm{s} + \pi_{8i}72\mathrm{s} + \pi_{9i}96\mathrm{s} + \pi_{10i}120\mathrm{s} + e_{ti}$$

Analysis of dominant and non-dominant limb vertical stiffness and impedance revealed that running intensity did not contribute to any of the variability observed during the match simulation. Initial analysis of the contribution of all five time intervals to SJ height revealed that when accounting for the running intensity performed during all five time intervals, the 96s preceding the testing interval was positively associated with SJ height (*Co-f* =0.23, *p*=.047), while the 120s preceding was negatively associated with SJ height (*Co-f* =-0.252, *p*=.043). Secondary analysis, performed after dropping non-significant time intervals and retaining only 96s and 120s intervals in the model, resulted in a small amount of the variability in SJ height being accounted for by each time interval (96s: *Co-f* =0.002, *p*=.001; 120s: *Co-f* =-0.001, *p*=.004). Tertiary analysis of SJ revealed that the running intensity during the final 96s and 120s were not associated with the SJ variability observed.

Initial analysis of the contribution of all five time intervals to $_{m}$CMJ height revealed that when accounting for the running intensity performed during all five time intervals, the 96s preceding the testing interval was positively associated with $_{m}$CMJ height (*Co-f* =0.23, *p*=.047), while the 120s preceding were negatively associated with $_{m}$CMJ height (*Co-f* =-0.252, *p*=.043). Secondary analysis, performed after dropping non-significant time intervals with only 96 and 120s intervals remaining in the model, resulted in a small amount of the variability being accounted for by each time interval (96s: *Co-f* =0.203, *p*=.00; 120s: *Co-f* =-0.12, *p*=.004). Tertiary analysis of $_{m}$CMJ revealed that the running intensity during the final 96s (*Co-f* =0.038, *p*=.015), but not the running intensity during the120s preceding testing (*Co-f* =0.011, *p*=.424), was associated with the performance variability observed.

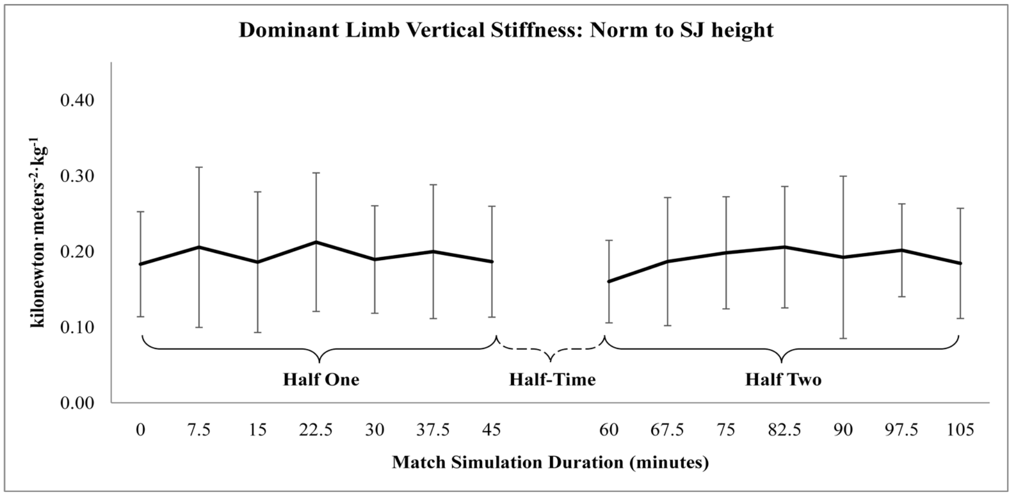
Analysis of Movement Mechanics Normalized to Jump Height

Vertical stiffness and vertical impedance of the dominant and non-dominant limbs were re-analyzed after normalizing to the landing height of the jump immediately preceding the phase of interest. Thus, vertical stiffness was normalized to SJ height (Figures 24 and 25), and vertical impedance was normalized to $_{m}$CMJ height (Figures 26 and 27). Each variable was subsequently analyzed separately for each limb utilizing the same univariate model previously applied (Statistical Model 1). This analysis (Table 22) revealed no time-related changes with soccer match simulation duration.

Table 32: Vertical stiffness and impedance normalized to jump height of preceding movement.

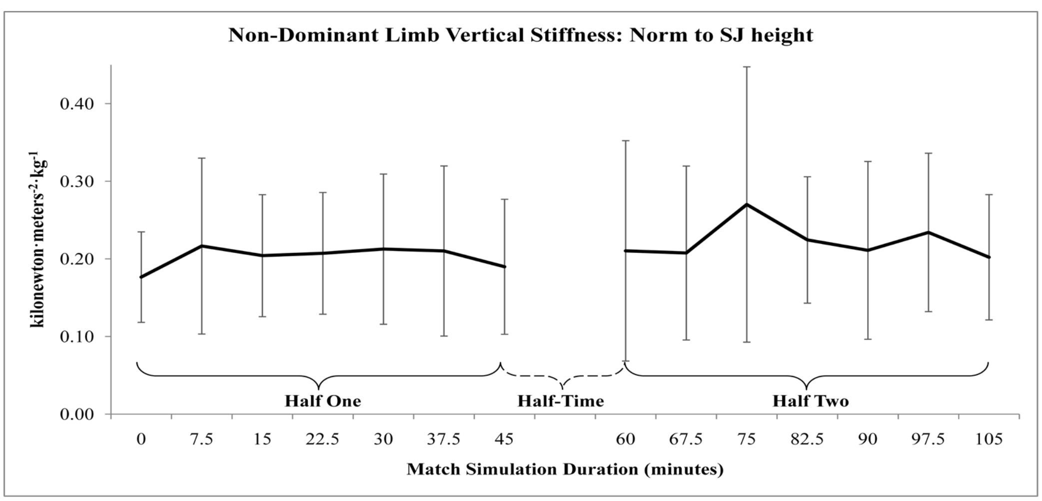
Variable	π_{0i}	$\pi_{1i}(\text{time})$	$\pi_{2i}(\text{time2})$	$\pi_{3i}(\text{D})$	$\pi_{4i}(\text{D} * \text{time})$	$\pi_{5i}(\text{D} * \text{time2})$
DStiffness	**0.198, .00**	0.002, .89	-0.000, .77	-0.021, .52	0.013, .55	-0.001, .62
NStiffness	**0.211, .00**	-0.000, .97	-0.00, .91	-0.012, .77	0.021, .46	-0.000, .46
DImped	**0.834, .00**	0025, .80	-0.004, .79	-0.004, .99	0.018, .91	-0.003, .90
NImped	**1.089, .00**	-0.056, .69	0.005, .77	-0.192, .49	0.161, .40	-0.688, .50

Figure 24: Dominant limb vertical stiffness normalized to SJ height.



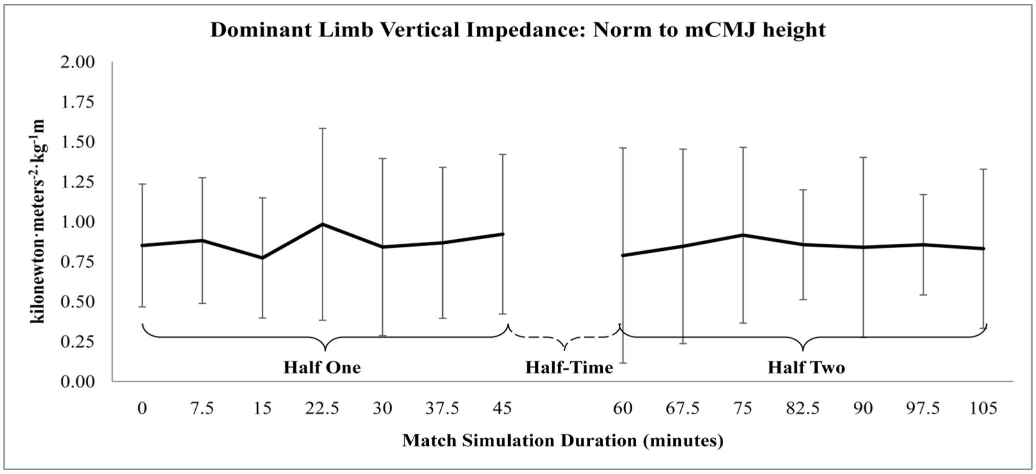
	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
DstiffHT	0.183	0.205	0.186	0.212	0.189	0.200	0.186		0.160	0.187	0.198	0.206	0.192	0.201	0.184
DstiffHT	0.069	0.106	0.093	0.092	0.071	0.088	0.073		0.055	0.085	0.074	0.080	0.107	0.061	0.073

Figure 25: Non-dominant limb vertical stiffness normalized to SJ height.



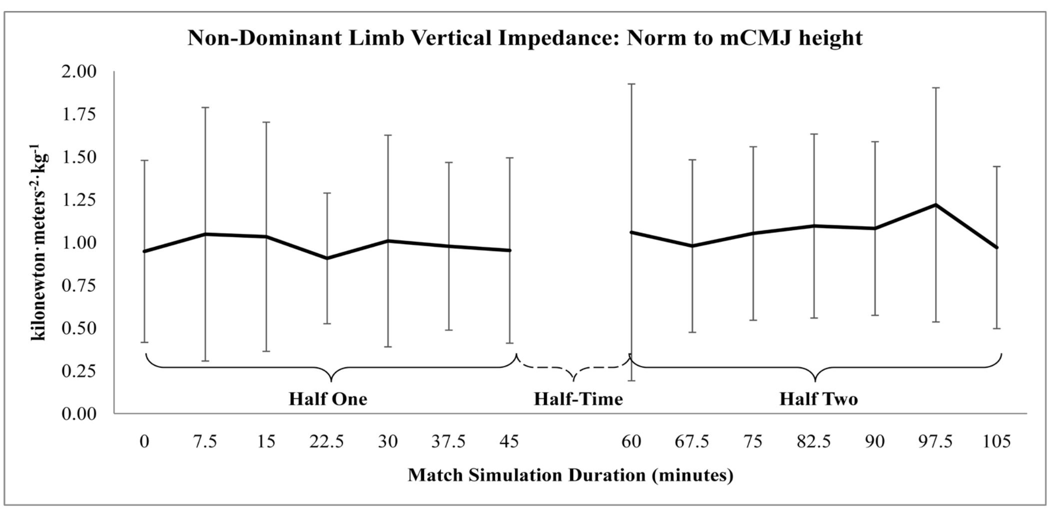
	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
NstiffHT	0.177	0.217	0.204	0.207	0.213	0.210	0.190		0.210	0.208	0.270	0.224	0.211	0.234	0.202
NstiffHT	0.058	0.113	0.079	0.078	0.097	0.110	0.087		0.142	0.112	0.177	0.081	0.115	0.102	0.081

Figure 26: Dominant limb vertical impedance normalized to $_{m}$CMJ height.



	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
DimpedHT	0.850	0.881	0.772	0.983	0.840	0.867	0.921		0.788	0.845	0.915	0.855	0.839	0.855	0.830
DimpedHT	0.384	0.393	0.376	0.600	0.554	0.472	0.499		0.673	0.609	0.550	0.343	0.563	0.314	0.498

Figure 27: Non-dominant limb vertical impedance normalized $_{m}$CMJ height.



	Half One								Half Two						
	0	**7.5**	**15**	**22.5**	**30**	**37.5**	**45**		**60**	**67.5**	**75**	**82.5**	**90**	**97.5**	**105**
NimpedHT	0.947	1.047	1.033	0.906	1.008	0.977	0.952		1.058	0.978	1.052	1.095	1.081	1.219	0.969
NimpedHT	0.532	0.740	0.669	0.381	0.618	0.490	0.541		0.867	0.504	0.507	0.537	0.507	0.684	0.473

Analysis of Contributors to Vertical Stiffness and Impedance

Lower extremity vertical stiffness and vertical impedance are calculated in the same manner as peak vGRF relative to peak center of mass displacement (COM). With only two constituent components, the maintenance of vertical stiffness and impedance implies the effective modulation of one, or both. In order to explore this possibility both vGRF and COM displacement were plotted for vertical stiffness and impedance in both limbs separately. Subjective analysis of these plots indicates that vGRF increased with soccer match simulation duration. This appears consistent in both stiffness and impedance and across both limbs. In contrast, COM displacement appears to respond differentially according to task phase and limb. For vertical stiffness it appears that COM displacement may have decreased slightly with exercise duration, while for the non-dominant limb the decrease appears to be both greater in magnitude and more absent of the fluctuation that characterizes COM displacement in dominant limb vertical stiffness. For vertical impedance, there appears to be a similar response across limbs, with a degree of fluctuation accompanying exercise duration. Statistical analysis of the potential time-related change and subsequent contribution of vGRF and COM displacement to the maintenance of stiffness and impedance observed is beyond the scope of the current analysis. However, these subjective analyses cause speculation that coordinative changes may have varied according to limb and task phase allowing for the maintenance of vertical stiffness and impedance with increasing soccer match simulation duration.

Figure 28: Contribution of vGRF and COM displacement to dominant limb vertical stiffness.

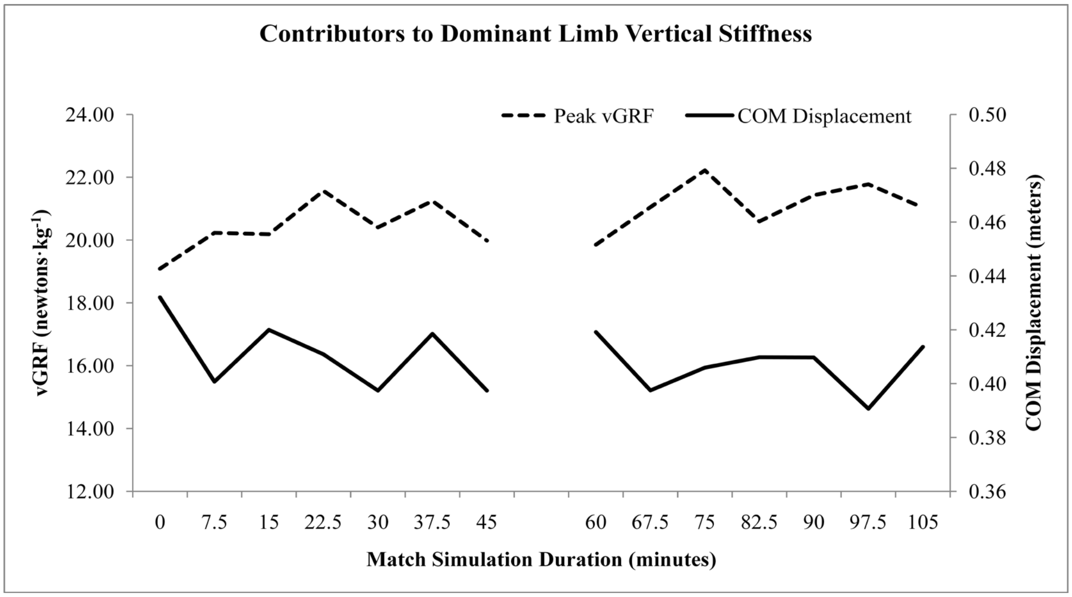


Figure 29: Contribution of vGRF and COM displacement to non-dominant limb vertical stiffness.

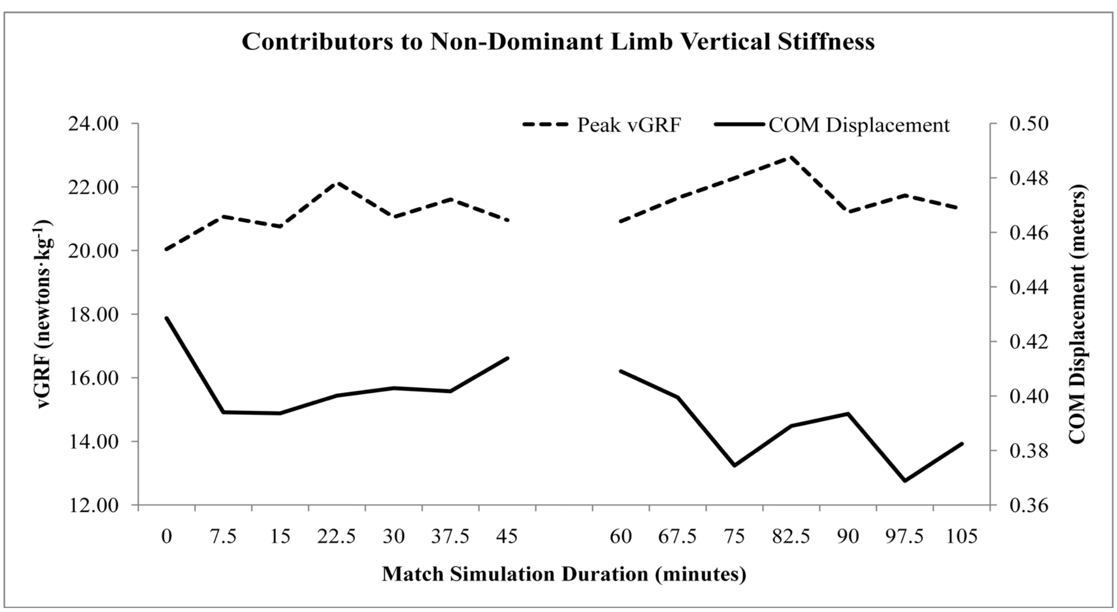


Figure 30: Contribution of vGRF and COM displacement to dominant limb vertical impedance.

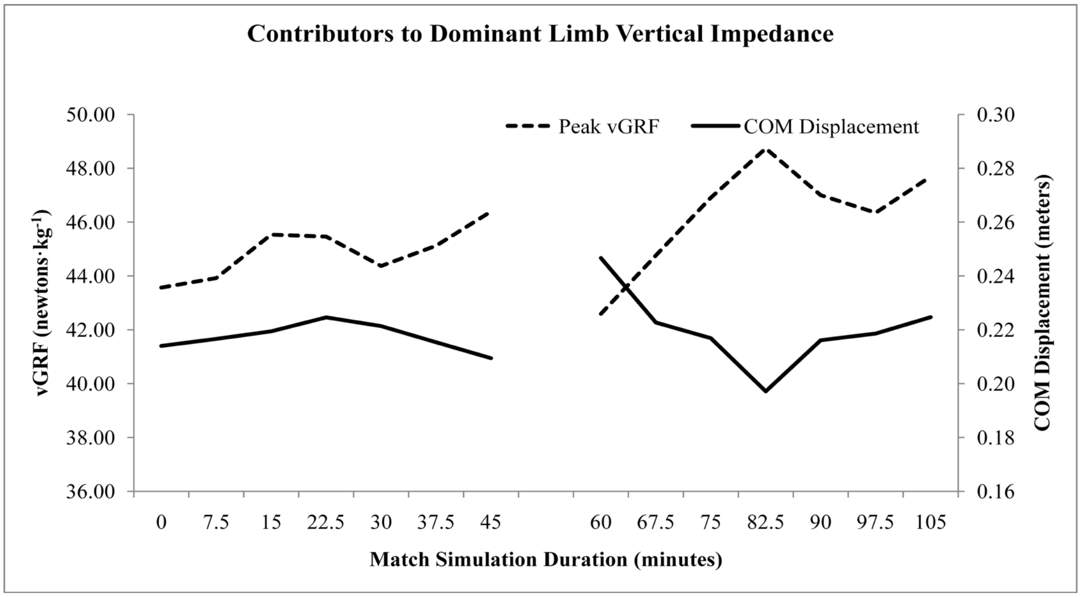
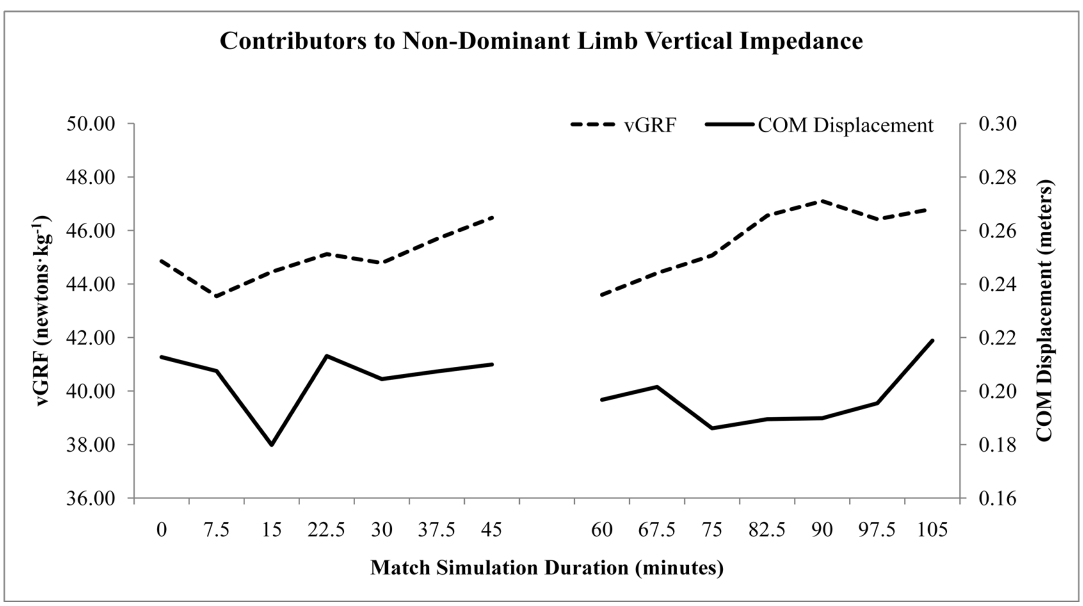


Figure 31: Contribution of vGRF and COM displacement to non-dominant limb vertical impedance.



CHAPTER V

DISCUSSION

The primary objective of this study was to determine if lower extremity function was significantly affected by exercise simulating the demands of a soccer match that has been individually prescribed to the participant's soccer-specific fitness level. To this end four hypotheses examining the progressive changes in movement mechanics and performance during the soccer match simulation were proposed. The primary finding that is consistent with the proposed hypotheses is that rating of perceived exertion (RPE) changed significantly across all time-related analyses of soccer match simulation duration; RPE values were higher in the second half compared to the first, and a greater rate of increase was observed during the second half compared to the first. The significant increase in RPE, as well as the decrease in performance components integrated into the 505 test for agility (cutting and sprint speed) with match simulation duration is indicative of increasing physical stress.fatigue, defined as a decline in performance due to intense, repeated bouts of exercise (Allen, Lamb, & Westerblad, 2008). In contrast to these observations, all performance and biomechanical outcomes of the integrated jump (vertical stiffness and impedance, and squat jump and modified counter movement jump height performance) were unchanged with soccer match simulation duration. The following discussion will initially focus on the physical and physiological demands of the individualized soccer match simulation. Thereafter, discussion will focus on the progressive effects of the match simulation on performance and movement mechanics.

Physical and Physiological Demands of the Individualized Soccer Match Simulation

An important development of this study is the prescription of a soccer match simulation to soccer-specific fitness level, and its ability to effectively replicate the demands of an actual match. The high subjective rating of the soccer match simulation relative to an actual match (8.69 ±0.59, with a score of 10 being exactly like a match) provided by the current subjects suggests that the match simulation effectively replicated an actual soccer match. This is corroborated by examination of the current subjects' performance relative to previous literature which was the basis for the development of the individualized soccer match simulation. Specifically, subjects in the current study performed in a similar manner during soccer-specific fitness testing to their professional counterparts (Krustrup et al., 2005; Mohr et al., 2003) resulting in similar match simulation distances.

YYIR1 Performance and Demands of the Soccer Match Simulation

Comparison of distance run during the YYIR1, which served as the basis for exercise prescription for the soccer match simulation, revealed that both male and female subjects performed in a comparable manner to their professional counterparts (see Table 23). In the present study, females ran an average distance of 1,276.67 ±306.28 meters, ranging from 800 to 1800 meters. This is similar to previous analyses of YYIR1 performance in female professional players who ran an average of 1,379 meters, ranging from a low of 600 meters to a high of 1,960 meters (Krustrup et al., 2005). The male participants in the study performed yet more closely to their professional counterparts, running an average distance of 2,283 (±393), compared to elite and moderate level professionals who ran an average distance of 2,260 (±800) and 2,040 (±600) meters (Mohr et al., 2003), respectively.

Table 33: Projected match simulation distances for female and male professionals, compared to match simulation distance covered during the current study.

[All running distances are in meters and expressed as mean (±sd). The YYIR1 reported for female professionals via Krustrup et al. (Krustrup et al., 2005) and male professionals via Mohr et al. (Mohr et al., 2003) with projected match simulation distances for female and male professionals calculated via reported YYIR1 performance, respectively. Male and female subject YYIR1 and match simulation distances reflect the distances run in current study.]

	Female Professionals	**Female Subjects**	**Male Professionals (elite)**	**Male Professionals (moderate)**	**Male Subjects**
YYIR1	1,379 (600-1960)	1,276.67 (±393)	2,260 (±800)	2,040 (±600)	2,283 (±393)
Match Simulation Distance	10,107.26 (9,463.99-10,750.53)	9,237.78 (±288.98)	11,025.46 (±748.35)	10,800.97 (±561.06)	11,093.26 (±369.52)

Performance in the YYIR1 test resulted in an average match simulation distance of 9,237.78 ±288.98 and 11,093.26 ±369.02 meters for females and males, respectively (Table 23). Comparison with predicted match simulation distance in female professionals, calculated via the range of YYIR1 performance reported by Krustrup et al. (Krustrup et al., 2005), ranged from 9,463.99 to 10,750.53 meters, with a mean of 10,107.26 meters. Comparison of these values indicates that females participating in the current study ran 8.6% less total distance than was predicted for the female professionals. The elite amateur males participating in this study ran a nearly identical distance to that predicted for elite and moderate level professionals, respectively, of 11,025.46 (±748.35) and 10,800.97 (±561.06) meters, calculated via mean and standard deviations of reported YYIR1 performance via Mohr et al. (Mohr et al., 2003).

The relationship between YYIR1 and total distance run during the soccer match simulation is perpetuated in sub-maximal running speeds (Table 24) and distance covered across the spectrum of sub-maximal running speeds (Table 25). These results further reflect similarities between the current study sample and the predicted match simulation performance via published data for male and female professionals (Krustrup et al., 2005; Mohr et al., 2003). For the female subjects this difference is characterized by slightly lower sub-maximal running speeds relative to the mean extrapolated values reported via Krustrup et al. (Krustrup et al., 2005) , but within the range of low and high performers. Relative to the mean, female subjects in this study covered approximately 1.4% less distance at each sub-maximal running speed than that predicted for their professional counterparts: walk=1.39%, jog=1.41%, low=1.40%, moderate=1.42%, and high 1.44%. In male subjects, comparison with elite level professionals reveals that male subjects differed by less than 0.01% across sub-maximal running speeds, while comparison with projected running speeds for the moderate level professionals demonstrated an approximate 2.5% difference (walk=2.30%, jog=2.45%, low=2.26%, moderate=2.84%, and high 2.57%). This is counter to previous research that revealed elite professionals cover approximately 5% greater total distance than moderate level professionals (Mohr et al., 2003; Tumilty, 1993). Collectively these findings indicate that the subjects participating in the current study were of similar soccer-specific fitness level to their professional counterparts, and thereby similar match simulation profiles.

Table 34: Projected match simulation running speeds in female and male professionals, and match simulation running speeds prescribed in the current study.

[All running speeds are in $m \cdot s^{-1}$, and expressed as mean (±sd). Female professional calculations were made via mean and range (low and high) of performance for YYIR1 performance as reported by Krustrup et al. (Krustrup et al., 2005). Male professional calculations were made via mean, plus and minus one standard deviation of YYIR1 distance as reported by Mohr et al. (Mohr et al., 2003). Both male and female subject data is expressed as mean (SD).]

	Walk	Jog	Low	Moderate	High
Professional Females	1.27 (1.17-1.34)	2.13 (1.96-2.25)	3.08 (2.83-3.25)	3.84 (3.52-4.05)	4.61 (4.23-4.86)
Female Participants	1.25 (±0.04)	2.11 (±0.07)	3.04 (±0.10)	3.78 (±0.12)	4.55 (±0.14)
Elite-Level Professionals	1.38 (±0.10)	2.32 (±0.17)	3.35 (±0.25)	4.17 (±0.07)	5.01 (±0.36)
Moderate-Level Professionals	1.35 (±0.07)	2.27 (±0.12)	3.27 (±0.17)	4.08 (±0.22)	4.90 (±0.25)
Male Participants	1.38 (±0.05)	2.32 (±0.08)	3.35 (±0.12)	4.17 (±0.15)	5.01 (±0.18)

Table 35: Projected match simulation distances in female and male professionals compared to match simulation distances covered in the current study.

[All data in meters. Projections of female professional match simulation distances were made via mean and range (low and high) performance during the YYIR1 performance from data reported by Krustrup et al. (Krustrup et al., 2005) and are expressed as mean (low-high). Projections of ,ale professional match simulation distances were made viapeformance during the YYIR1 from data reported by Mohr et al. (Mohr et al., 2003) as mean and sd, and are here expressed as mean (±sd). Male and female subject data are expressed as mean (±sd) from running distances during the individualized soccer match simulation.]

	Walk	Jog	Low	Moderate	High
Professional Females	1602 (1470-1689)	1434 (1316-1512)	3624 (3325-3822)	1933 (1774-2039)	775 (711-817)
Female Participants	1580 (±49.3)	1414 (±44.4)	3574 (±111.8)	1906 (±59.7)	764 (±23.8)
Elite-Level Professionals	1741 (±128.7)	1558 (±115.2)	3939 (±291.1)	2102 (±155.3)	842 (±62.2)
Moderate-Level Professionals	1702 (±90.4)	1524 (±80.9)	3851 (±204.5)	2054 (±109.1)	823 (±43.7)
Male Participants	1742 (±64.1)	1559 (±57.3)	3940 (±144.9)	2102 (±77.3)	842 (±31.1)

The high level of YYIR1 performance observed in the current male sample as compared to professional players leads to some disparity in regards to expectations that exist for playing level and fitness level (Mohr et al., 2003; Tumilty, 1993), and may be the result of several components. First, of the twelve male participants in the current study three were full-backs and nine were midfielders, a cohort who has been observed to perform consistently higher in aerobic based fitness tests (Reilly et al., 2000) and the YYIR1 test (Krustrup et al., 2003; Mohr et al., 2003) than attackers and central defenders. In comparison, the females participating in the study were more evenly distributed with five midfielders, four forwards, one full-back and two central defenders, speculatively contributing to the slightly lower performance relative to their professional counterparts. Second, subject age may be a contributing factor as it has been observed that aerobic performance, measured via maximal oxygen uptake in junior elite athletes (age: 17.6 ±0.9 years) was not significantly different than their older elite counterparts (age: 24.2 ±4.7 years) (Hoff, Kemi, & Helgerud, 2005). As YYIR1 performance is significantly correlated to aerobic performance in males ($r=0.79$, $p< .05$) (Krustrup et al., 2003), the current population mean age of 19.66 ±1.50 compared to that of 26.4 ±0.9 years in the professional players (Mohr et al., 2003) is similar in magnitude to the difference observed by Hoff et al. (Hoff et al., 2005). Thus, while the subjects examined by Mohr et al. (Mohr et al., 2003) were of a higher playing standard than the current subjects, differences in fitness level may be delimited by the younger age of subjects in the current study. Third, the time of season at which the subjects performed the YYIR1 test may have played a role, as it has been observed that YYIR1 performance fluctuates across the preparation and competitive phases of the season (Krustrup et al., 2003). The current study was purposely conducted during the 1 to 2 weeks prior to the start of the NCAA soccer preseason, a time when it is anticipated that players are approaching a high-level of fitness in preparation for the college preseason which is remarkably short, [i.e. two-weeks in duration compared to the 6 to 8 week preseason that is more common in the professional game (Morgan & Oberlander, 2001; Woods et al., 2002)]. Comparison of YYIR1 performance in the current male population with seasonal performance is supportive of this as the current population's performance in the YYIR1 most closely reflects that observed at the start of the season (2211 ±70 meters) where fitness level was highest in the professional players examined compared to preparation (1760 ±59 meters) and competition (2103 ±68 meters) periods (Krustrup et al., 2003). Finally, the YYIR1 test in the current study was conducted in a controlled environment, with a relatively constant ambient temperature, and a controlled running surface which may be in contrast to those studies conducted by Mohr and Krustrup (Krustrup et al., 2005; Mohr et al., 2003) where the characteristics of the environment in which the YYIR1 was performed are not reported.

The physiological load of the individualized soccer match simulation was characterized by the heart rate response, and in this manner the individualized soccer match simulation demonstrates a similar response, but slightly lower response to that observed in match analyses (Bangsbo, 1994b; Ekblom, 1986; Helgerud et al., 2001; Krustrup et al., 2005). For the females analyzed in the current study, the observed mean heart rate (158 ±14.68 bpm) and peak heart rates ranging from 172 to 208 bpm (N=8) were comparable to match analyses where mean match HR was 167 bpm and a peak HR of 171-205 were observed (Krustrup et al., 2005). Unfortunately, recording of female heart rate data during the YYIR1 and the match simulation were not reliably recorded on all subjects and thus is incomplete, not allowing for analysis of heart rate relative to HR_{peak} during the YYIR1. Analysis of males in the current study revealed an average absolute heart rate of 148.30 ±11.99 bpm which equated to a relative HR of 76.65 ±5.00% HR_{peak}. The peak heart rates observed were 177.88 ±10.22 and 174.30 ±8.08 bpm equating to relative peak heart rates of 92.57 ±5.19 and 89.57 ±3.53% HR_{peak} for half one and half two, respectively. These values are slightly lower than previous match analyses where it has been observed that substantial portions of the match are at 80% HR_{max} and frequently above 90% HR_{max} (Bangsbo, 1994b; Ekblom, 1986; Tumilty, 1993) with values in excess of 98% HR_{max} reported (Bangsbo, 1994b; Krustrup et al., 2006). The difference appears to be somewhat systematic between actual match analyses and the soccer match simulation and is speculatively the result of primarily environmental factors, foremost, the controlled ambient temperature of the testing, and the lack of psychological stressors and accompanying physiological responses that are inherent in a competitive match and lacking in the controlled environment of the current analysis.

Summary

The slightly lower physiological response (quantified via HR) to the match simulation is a short-coming of the simulation, and speculatively indicates that the ability to account for such contributors as psychological stress, and changing locomotion pattern (backwards running, side-shuffling, and soccer-specific movements incorporating the ball) may be an important component to integrate in future research. While it was anticipated (although never hypothesized) that the match simulation prescription would account for differences in playing level, this was not the case in the males. As such this does not prevent the potential use of the match simulation for soccer-specific research in other populations of varying age and playing level.

Progressive Effects of an Individualized Soccer Match Simulation

The individualized soccer match simulation was specifically designed to allow for a progressive analysis of movement, and performance. To this end all testing was integrated into the demands of the match simulation at 7.5-minute intervals and subsequently examined via statistical analyses of time-related change and between half comparisons. The progressive changes observed in RPE most closely emulate the proposed hypotheses albeit in a manner at times in contrast to the hypothesized direction of change. In contrast, the two tasks integrated into the soccer match simulation: 1) the 505 test of agility and 2) integrated jump task that allowed for analysis of performance and movement based hypotheses, revealed a lack of time-related changes. Further examination of the components integral to the integrated jump task (vertical stiffness and impedance, and squat jump and modified counter movement jump height) indicate the possible role of running intensity in this variation, and perhaps more significantly that individual differences existed in the subjects' response to soccer match simulation duration.

Time-Related Changes in Rating of Perceived Exertion

The rise in RPE with increasing exercise duration is indicative that subjective physical stress increased with soccer match simulation duration in a manner similar to exhaustive running. This is evident in the finding that the RPE at the end of the soccer match simulation (17.21 ±1.67) was only slightly lower than that observed during exhaustive running of 18.9 ±1.1 and 18.2 ±1.7 in subjects categorized as having moderate and high aerobic fitness (Garcin, Mille-Hamard, & Billat, 2004). Additionally, several of the subjects in the current study were speculatively close to maximal effort at the end of the soccer match simulation with the final RPE reported in nine of the twenty-four subjects being greater than 18 and seven reporting an RPE of 19 or higher. The increase in RPE observed in the current study, which demonstrated a first half increase from 10.67 to 15.42, a second half increase from 12.58 to 17.21 and a significantly higher rate of increase in the latter segments of the second half compared to the first, substantiates the suggestion that subjective physical stress was great in the current soccer match simulation. Additionally, as RPE is a scale existing from 6 to 20, it is possible that a ceiling effect may have occurred with exercise duration in the second half such that a slower change, and rate of change with exercise duration occurred due to the fact that RPE started higher initially, then may only increase to a pre-determined level. The consistent rise in RPE results in speculation that the half-time interval may have attenuated a continued climb in RPE at an even higher rate than that observed in the analyses. The incorporation of an approximate 4-minute light re-warming period towards the end of the 15-minute half-time break was made to ensure performance at the start of half two. While the re-warm-up may have attenuated performance decrements at the start of the second half due to cooling (Lovell, Kirke, Siegler, McNaughton, & Greig, 2007; Mohr, Krustrup, Nybo, Jung Neilsen, & Bangsbo, 2004), it may have contributed to the findings in a couple of ways. First, it may have resulted in a slightly higher RPE value at the start of the first half than may have been reported if the subjects rested for the full 15-minute interval. Second, it may have attenuated a faster climb in RPE during the subsequent time intervals by better preparing the subjects for their return to high-intensity exercise.

Comparisons of RPE values and the corresponding increases observed with exercise duration in the current study indicate that the current analysis resulted in a higher level of subjective stress than previous soccer match simulation research (Gleeson et al., 1998; M. P. Greig et al., 2006; Oliver et al., 2008). This is most evident in comparing the current study's findings to soccer simulated treadmill running where a RPE value of 9 ±1 was observed at the onset of exercise, but a peak RPE value of 12 ±2 during the final 15-minutes of the soccer match simulation was observed (M. P. Greig et al., 2006); indicating a reduced amount of subjective stress compared to the current analysis. Interestingly, this modest change in RPE in their study was accompanied by a significant increase in total and peak surface EMG activity of the rectus femoris indicating that the muscle was significantly affected by the soccer simulated exercise (M. P. Greig et al., 2006). The current data more closely resembles a second soccer match simulation study where similar increases in RPE with exercise duration [17.21 ±1.67 v ~16±2 EU's (Gleeson et al., 1998)] were accompanied by decrements in concentric isokinetic muscle strength in both the quadriceps and hamstring muscles, as well as increases in electromechanical delay (Gleeson et al., 1998). Based on these collective studies one may speculate that similar, and possibly greater, decrements in isolated muscle strength and muscle mechanical properties may have accompanied the soccer simulated exercise of this individualized soccer match simulation.

Sprint and Cutting Performance

The decrement in isolated muscle performance observed in previous studies is consistent with findings in the current study where a decrease in sprint and cutting performance with increasing match simulation duration was observed. This was characterized by a decrease in sprint speed of 0.090 $m \cdot s^{-1}$ each 7.5-minute interval resulting in a decrease in running speed across the first half from a peak of 4.42 $m \cdot s^{-1}$ to 4.26 $m \cdot s^{-1}$ during the first half, with a similar decrement observed during the second half from 4.26 $m \cdot s^{-1}$ to 4.30 $m \cdot s^{-1}$. The lack of time-related changes in the rate of change in sprint performance between halves is indicative that the rate of decrease in sprint speed was consistent between halves. Comparison of the current findings with the lone previous match simulation research examining sprint speed, where no decrement in sprint velocity was observed (Oliver et al., 2008), is illustrative of the increased demands of the individualized soccer match simulation compared to previous match simulation research.

While the current study is the first of its kind to analyze cutting performance, kinematic analyses of cutting during a treadmill soccer match simulation was previously conducted by Greig et al. (M. P. Greig, 2009) without addressing changes in cutting speed. This analysis demonstrated significant time-related changes in movement mechanics, with an increase in knee flexion and total knee ROM with exercise duration that was accompanied by an increase in valgus motion of the plant foot in cutting at the end of each half (M. P. Greig, 2009). The aforementioned analysis examined cutting in the preferred kicking limb only, therein ignoring the potential for limb asymmetry. Conversely, the current study examined cutting performance in both the dominant and non-dominant limb, and results suggest that each limb responds differently during the soccer match simulation. While a direct comparison of cutting between the dominant and non-dominant limb performance is beyond the scope of the current analysis, notable differences are evident. Among these is the subjective observation that non-dominant limb cutting was consistently slower than dominant limb cutting performance (Figures 13 and 14), and that changes in cutting performance differed from the dominant to non-dominant limb. The latter difference was characterized by a decreasing rate of change with match simulation duration, and between half differences in the change and rate of change in dominant limb cutting that was not observed in the non-dominant limb. Jointly, these findings are indicative of the need for further analyses of limb asymmetry in soccer players and the need to examine performance and movement mechanics in a unilateral manner. This is of specific importance given the finding that limb asymmetry may contribute to an increased rate of injury (Plisky, Rauh, Kaminski, & Underwood, 2006; Wong et al., 2007) and that soccer players demonstrate a high prevalence of limb asymmetry (Carey et al., 2001; Gioftsidou, Beneka, Malliou, Pafis, & Godolias, 2006; Rahnama, Lees, & Bambaecichi, 2005; Voutselas, Papanikolaou, Soulas, & Famisis, 2007; Wong et al., 2007).

A final noteworthy and consistent characteristic of between half analyses of sprinting and cutting performance was a decrease in performance following the half-time interval relative to the start of the first half. This finding persisted in spite of a re-warming period towards the end of the half designed to counter previous observations, and in line with research that re-warming at half-time diminished performance decrements (Mohr et al., 2004). While a recovery towards baseline performance was observed, it may be concluded that the half-time interval was insufficient to allow for full recovery. An important subjective observation is that both group and individual subject data reveal an increase in sprint and cutting performance during the final trials of both the first and second halves relative to the preceding trials. Speculatively this increase in performance is the result of increasing motivation as the subjects approached the end of the measurement period(s). This latter observation elucidates a potential need in future research to attempt to control for increasing subject motivation that may occur towards the end of each half of play.

Time-Related Changes in the Integrated Jump Task

Analysis of the integrated jump (based on the variables: SJ height, $_{m}$CMJ height, and vertical stiffness and impedance) was characterized by a distinct lack of time-related change. This finding was counter to the proposed hypothesis for mCMJ, consistent with the hypothesis for SJ, and in contrast to the previously discussed findings of RPE and sprinting and cutting performance, where physical stress appears to progress with soccer match simulation duration. In all comparisons, the changes in RPE and sprint performance observed in the current study were equal, if not greater than, the changes observed in previous match simulation research resulting in significant changes. Therefore, a lack of findings for the components of the integrated jump is curious, and leads to the possibility that the subjects were able to maintain jump height performance during the match simulation, or that the variability subjectively observed in the components of the integrated jump contributed to the lack of significant time-related change.

When comparing the current study's findings with previous soccer match simulation research, a number of factors that might explain the lack of time-related change were considered. First, for SJ and $_{m}$CMJ performance the lack of time-related change in the present study is in contrast to previous research where no decrease in sprint velocity was accompanied by significant decrement across jumping modalities (squat jump, counter movement jump, and drop jump), as well as changes in muscle mechanical properties during high-velocity SSC work (Oliver et al., 2008). Second, for vertical stiffness and impedance, previous research indicates that soccer match simulated exercise is accompanied by changes in muscle strength (M. Greig, 2008; M. Greig & Siegler, 2009) and activation (M. Greig, 2008; M. Greig & Siegler, 2009; Oliver et al., 2008), as well as an increase in electromechanical delay (Gleeson et al., 1998). These findings suggest that similar decrements in jump performance, and muscle strength and activation may have occurred during the current match simulation, but were speculatively not evident due to the complex nature of the integrated jump task.

The later comparison is of particular importance in light of examinations of vertical stiffness. The stretch-reflex response is integral to modulation of vertical stiffness and increasing muscle activation (Gollhofer et al., 1984; Komi, 2000; Komi & Gollhofer, 1997; Kyrolainen et al., 2005), and thereby impedance that is characterized by the same components. Thus, any delay in the mechanical response of the muscle, such as an increase in electromechanical delay similar to that observed in the aforementioned study where the RPE response was slightly lower than in the current study (Gleeson et al., 1998), would be manifest as decreasing vertical stiffness and impedance as the match simulation progressed. Additionally, an increase in muscle activation, as previously demonstrated by Greig et al. (M. P. Greig et al., 2006), suggests that it is unlikely that muscle activation was not affected in the current study where a much greater RPE response occurred. Previous analyses using prolonged (Avela & Komi, 1998a, 1998b) and exhaustive (Dutto & Smith, 2002) running, as well as acute sprinting (Morin et al., 2006) and sub-maximal drop jumps (Horita et al., 1996, 1999; Kuitunen et al., 2007) demonstrated decreases in muscle, joint, and vertical stiffness. Where lower extremity vertical stiffness alone has been analyzed results both decreases and maintenance of stiffness has been documented. In the aforementioned, Dutto and Smith and Kuitunen et al. (Dutto & Smith, 2002; Kuitunen et al., 2007), decreases in vertical stiffness were observed following exhaustive treadmill running and sub-maximal drop jumps, respectively. In contrast, sub-maximal squatting (Padua et al., 2006) and maximal drop jumps (Kuitunen et al., 2007) performed to exhaustion were not accompanied by changes in vertical stiffness. Thus, while the current findings are in contrast to the proposed hypotheses, the maintenance of vertical stiffness is plausible, and may represent both methodological differences in both the measurement of vertical stiffness, as well as the type of exercise that was performed by the subjects. Further research examining the possible differential response and modulation of lower extremity vertical stiffness to different modalities of exercise may elucidate potential contributors to the lack of change in vertical stiffness observed in the current and previous studies.

It may be that a short-coming of the current study is the use of vertical stiffness, the most global measure of stiffness (Brughelli & Cronin, 2008a; Hughes & Watkins, 2008), essentially a composite of the stiffness observed at the individual lower extremity joints of the hip, knee, and ankle. The result is that the contribution and modulation of joint stiffness across the lower extremity that contributed to the maintenance of vertical stiffness and impedance with increasing soccer match simulation was not examined. This suggestion is supported by analysis of hopping and counter movement jumping following fatiguing exercise demonstrating changing lower extremity coordinative patterns following fatiguing exercise (Bonnard et al., 1994; Orishimo & Kremenic, 2006a). For this reason, examination of individual joint stiffness contributions to performance and movement maintenance in complex tasks such as the integrated vertical jump presents an area for further research.

The design of the integrated jump task was purposeful in its ability to analyze the three different types of muscle action: concentric, stretch-shortening cycle (SSC), and eccentric, thus allowing for analysis of the differential effects of soccer match simulation duration on specific types of muscle action. Unfortunately, the complexity that accompanies the execution of the task may have resulted in a greater degree of variability that may have masked a significant change with exercise duration across all components of the integrated jump task. While it may be suggested that growing familiarity with the integrated jump task contributed to the lack of significant findings, this is not apparent in the statistical analysis as no increase in any components was evident. Therefore, two possible explanations for the lack of change across time were considered: 1) the variation in running intensity prior to the testing intervals contributed to performance inconsistency, and 2) movement and coordination variability diluted time-related changes. These concerns led to two exploratory analyses of these potential contributors to variability in performance and movement mechanics during the integrated jump task.

Integrated Jump Task: Contribution of Running Intensity

The structure of the match simulation resulted in within half variability in the running performed prior to each testing interval. This resulted in the potential that fluctuation in exercise demands in the intervals immediately prior to testing may have contributed to some of the variability observed in the integrated jump task. However, analysis of running intensity as a covariate across five time intervals revealed no significant contribution of the variability observed in vertical stiffness and impedance. Running intensity did account for a small amount of the change observed in the SJ and $_{m}$MCJ height, more so in the $_{m}$CMJ than SJ height. These findings are indicative of performance during higher SSC actions being more greatly affected by running intensity. Interestingly, these changes were associated with the running intensity during the 96 and 120s, but not shorter durations (24, 48, and 72s). Hence, exercise intensity over longer rather than shorter intervals may be more impactful to performance. This interpretation however is made cautiously as the contribution of running intensity at longer durations is more likely a result of the structure of the match simulation. Specifically, sufficient variability in running intensity may not have existed at the shorter durations, while increasing the duration of analysis leads to greater variability in the running intensity performed and therein the potential for elucidating differences (refer to Table 21). Regardless, these findings indicate that the exercise intensity preceding the testing interval contributes to performance variability, and plays a greater role in movements containing SSC work.

Integrated Jump Task: Movement and Coordination Variability

Comparison of the current findings with previous match simulation research results in speculation that changes in performance and movement mechanics may have been effectively masked by the complexity of the integrated jump task. Specifically, given the previously discussed findings of Gleeson et al. (Gleeson et al., 1998) where similar changes in RPE with intermittent running resulted in increases in electromechanical delay, one would expect that exercise of similar subjective demand would elicit a similar mechanical response ultimately reflected in both vertical stiffness and impedance. This may also be representative of a difference in the research approach, as the concentric hamstring muscle action analyzed previously, contrasts the more quadriceps dominant eccentric and SSC loading that characterized the integrated jump task. The expectation that change would occur is, however, reinforced via findings from soccer simulated treadmill running where neuromuscular changes were observed (M. P. Greig et al., 2006) and the fact that treadmill running has been shown to have a diminished effect relative to normal running (Gleeson et al., 1998). Together these findings strengthen speculation that the lack of a decrement in movement mechanics and jump performance in the current study may have been the result of coordination variability and the complexity that was inherent in the integrated jump task.

The initial observation that variability in integrated jump task performance may have contributed to the lack of time-related change was subsequently corroborated by calculations of the coefficient of variation across all variables. Subjectively, these indicate a higher degree of variability at each time point throughout the match simulation for all components of the integrated jump task. However, no discernible patterns appear evident in the fluctuation observed with match simulation duration. Exploration of the possible effect of task complexity resulting from the linking of the three phases, precipitated by the observation that vertical stiffness changed with drop height in jumping (Arampatzis, Schade et al., 2001), was analyzed by normalizing vertical stiffness and vertical impedance to the jump height achieved in the preceding action. This additional analysis revealed the same as the previous analyses, with no significant changes observed in vertical stiffness and impedance normalized to jump height in either the dominant or non-dominant limbs.

Subjective observations during the testing sessions demonstrated that the subjects were at a high level of physical stress towards the end of the match simulation. This was characterized by the subjects frequently performing the wrong jump sequence, landing on the non-test limb, or not being able to complete the jump successfully. The first two observations were noted to occur in several subjects towards the end of exercise, suggesting that exercise duration was accompanied by a cognitive decline in the subjects. While central and peripheral components of fatigue were not directly analyzed, the steady climb in RPE towards levels that, as previously discussed, are primarily observed in exhaustive exercise implies that the subjects were nearing exhaustion upon completion of the soccer match simulation. In looking at the number of jumps required at each testing interval, there is a clear increase in the number of failed attempts with exercise duration with the highest number of missed attempts during the second half (1.14) vs. the first half (0.80). Additionally, the largest number of missed attempts occurred in the final 30-

minutes of exercise, accounting for 53% of the missed jumps observed across the entire match simulation. As only the successful integrated jump attempts were accepted during testing, with the subjects repeating the task following a faulty attempt, it may be speculated that this limited the ability of these analysis to detect the hypothesized decreases in vertical stiffness and impedance.

It is important to consider for future research the possible contribution of intrinsic components to the match simulation that may have contributed to the higher CV values in the integrated jump task. Aside from the possible movement and performance variability inherent in the task, given the exploratory analysis of running intensity and the subsequent findings for SJ and mCMJ, it may be of interest to conduct further analyses of how running intensity contributed to the fluctuation in CV that is subjectively observed to occur during the soccer match simulation. In addition, analysis of the variance components for stiffness and impedance indicate that significant individual differences exist in the subject's time-related response to exercise duration. Variability at the individual level, evident via random effects, was observed in sprint and RPE as well, and may be indicative of a differential response of individual subjects to the match simulation.

Ultimately, these findings result in the persistence of two possible conclusions. That the complex coordination required by the integrated jump task resulted in sufficient variability as to diminish the possibility that time-related changes could be detected. Alternately, the components of the integrated jump task were not significantly diminished with increasing match simulation duration and the subjects were able to effectively maintain jump performance and movement mechanics even with increasing match simulation duration and the accompanying rise in physical stress. These findings further highlight the need for analysis of the modulation of lower extremity joint coordination of the ankle, knee, and hip during the match simulation. While it is beyond the scope of the current analysis, further examination of the modulation of lower extremity joint coordination during the integrated jump task requires consideration and may assist in understanding how coordination of complex tasks are modulated with soccer match simulation duration.

Summary

The exploration of further lower extremity coordinative components that may account for either the variability, or maintenance of performance and movement observed in the integrated jump task characteristics is beyond the scope of the current analyses. However, it is speculated that variability in movement mechanics and performance is a common component to sport and may rise and fall during a competitive match where complex tasks are integral to a high level of performance, in particular during dynamic and unpredictable sports such as soccer. Thus, speculatively, in some instances movement mechanics may be compromised for performance, and in others performance compromised for movement mechanics. Subjectively, this was observed in the current study where jump height appears to be at times compromised in order to allow for the task to be successfully completed, with the antithesis also observed. This may be representative of a fundamental difference inherent in the laboratory setting relative to competition where speculatively, performance maintenance may supersede movement mechanics leading to its inevitable compromise. Subjective examination of the contributing factors to vertical stiffness and impedance, vGRF and COM displacement, speculatively indicate that coordinative changes may have varied according to limb and task phase allowing for maintenance of vertical stiffness and impedance with increasing exercise duration. How lower extremity coordination was modulated is a focal point for further research and examination. Additionally, the observation that variability existed at the individual level across a number of the examined variables: RPE, sprint speed, stiffness, impedance and $_{m}$CMJ performance, may indicate a differential response to exercise duration among the subjects that should be explored in further study.

Limitations of Analysis

A potential limitation of the present study was the use of a univariate analysis. Although exercise duration appears to have no effect on movement mechanics and jump performance, additional more complex modeling may elucidate the potential contribution that noise at the individual level may have contributed to the lack of group differences with soccer match simulation duration. Significant individual level differences were persistent across variables and result in speculation that variability at the individual level may have resulted in the diluting of group level differences, thus decreasing the likelihood of time-related changes being detected is reflected by exploratory analyses of random effects. The significance of random effects must be interpreted with caution due to correlation between the subject level random effects (see Appendices 2-5: Tau as correlations) and small variances present in the univariate analyses of each variable. However, the need to focus further research on between subject differences is elucidated by exploratory T-analyses indicating that YYIR1 performance, years playing experience, and playing position were associated with the time-related changes observed across numerous variables. These findings indicate the potential that participants may respond differentially during the course of the soccer match simulation and precipitates speculation that further research is necessary to examine subject characteristics that may contribute to the differential response with exercise duration.

The ability to effectively simulate the physical demands of a soccer match will also have limitations relative to what actually occurs in a competitive match. The current study accounted for the increased physical demands of multi-directional actions such as shuffling and backwards running via the incorporation of slightly greater moderate intensity work than is typically observed during an actual soccer match. Additionally, the increase stress which accompanies the technical demands of dealing with the ball is accounted for by the match simulation incorporating a higher amount of maximal intensity work (sprinting) than is typically observed in match analyses. Perhaps the greatest limitation is the ability to incorporate, or account for the psychological stress that accompanies a competitive soccer match. An effort to account for decision-making and its accompanying reactionary and psychological components that are integral to competitive soccer was made via all sub-maximal running intensities being initiated on the command of the testers with the subjects responding accordingly.

Chapter Summary

The current analysis of the effects of an individualized soccer match simulation is characterized by several findings. Foremost is that the individualized soccer match simulation prescribed via YYIR1 performance successfully replicates the demands of a soccer match and these demands precipitated an increase in RPE that was accompanied by decreases in both sprinting and cutting speed with soccer match simulation duration. Several observations elucidate the need for further analysis. Among these is that dominant and non-dominant limb cutting responded differentially to exercise duration, and that intermittent exercise intensity may contribute some of the variability observed in jump performance. The lack of significant findings regarding jump performance and movement mechanics during the integrated jump task was counter to the proposed hypotheses and is cause for further examination of how lower extremity coordination between joints is modulated during complex tasks in order to maintain performance and movement mechanics.

These findings add to the current understanding of research regarding the response to soccer match simulated exercise by demonstrating the feasibility of individualizing soccer match demands to a participant's fitness level and integrating a progressive analysis of movement mechanics and performance. Additionally, the research demonstrates three primary areas for further exploration. The first is the role that intermittent exercise intensity may play in performance and movement mechanics of complex tasks during the course of soccer-simulated exercise. The second is examination of the extent in which dominant and non-dominant limbs respond differentially with exercise duration in soccer players and the potential contributors to limb asymmetry such as unilateral strength and power. The third is examination of the role individual lower extremity joint coordination plays in the maintenance of movement mechanics and performance during soccer simulated exercise. Finally, a more comprehensive analysis including kinetic, kinematic, and surface EMG analyses of complex tasks during the course of an individualized soccer match simulation may elucidate more completely the effects of soccer match simulated exercise on movement and performance.

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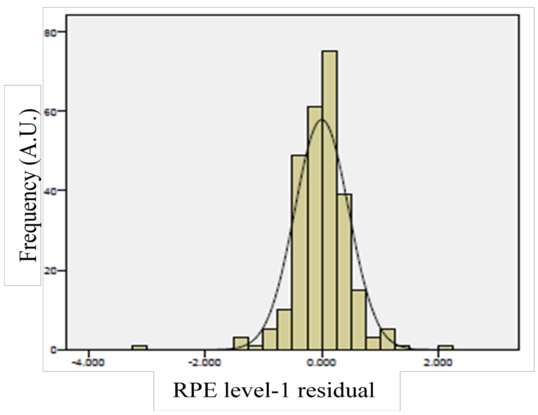
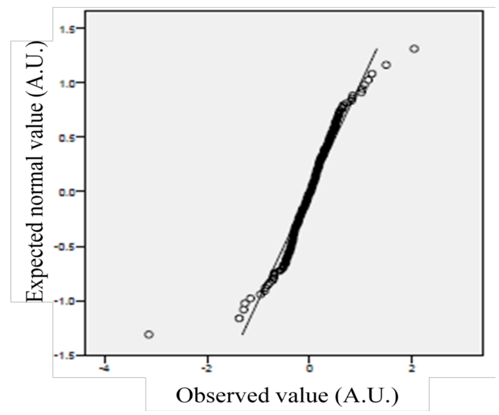
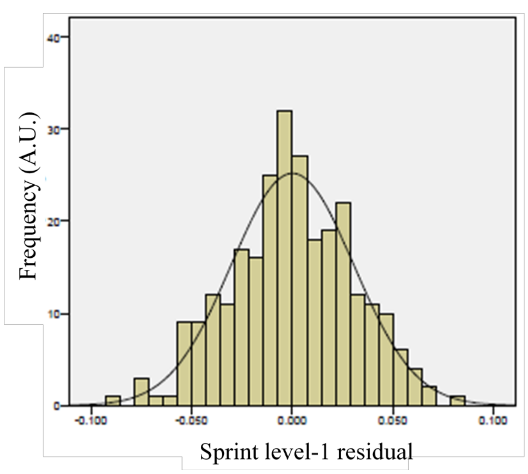
APPENDIX A: DATA ANALYSES OF ASSUMPTIONS OF NORMALITY AND HETEROGENEITY.

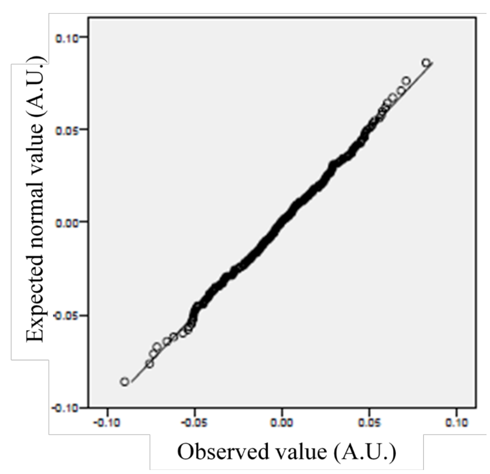
A1: Residual analysis of RPE: Histogram and Q-Q plots



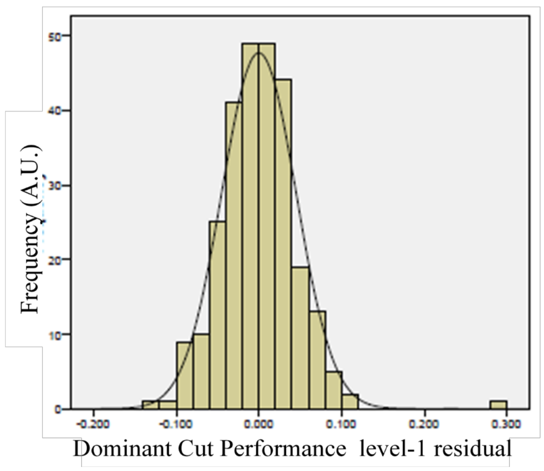


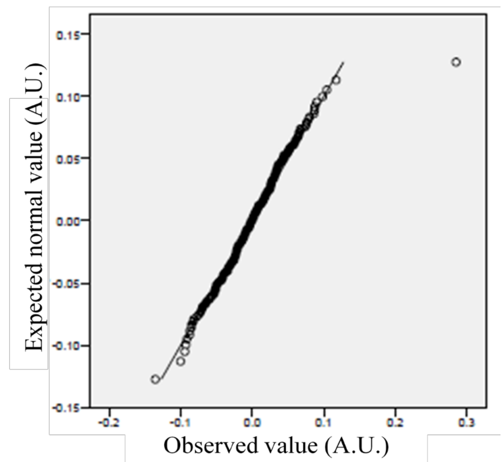
A2: Residual analysis of sprint performance: Histogram and Q-Q plots



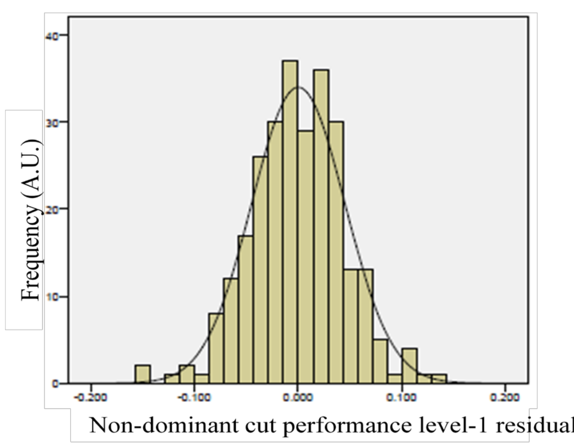


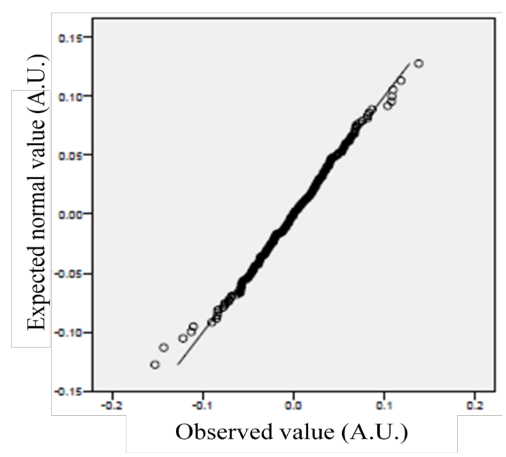
A3: Residual analysis of dominant limb cutting performance: Histogram and Q-Q plots



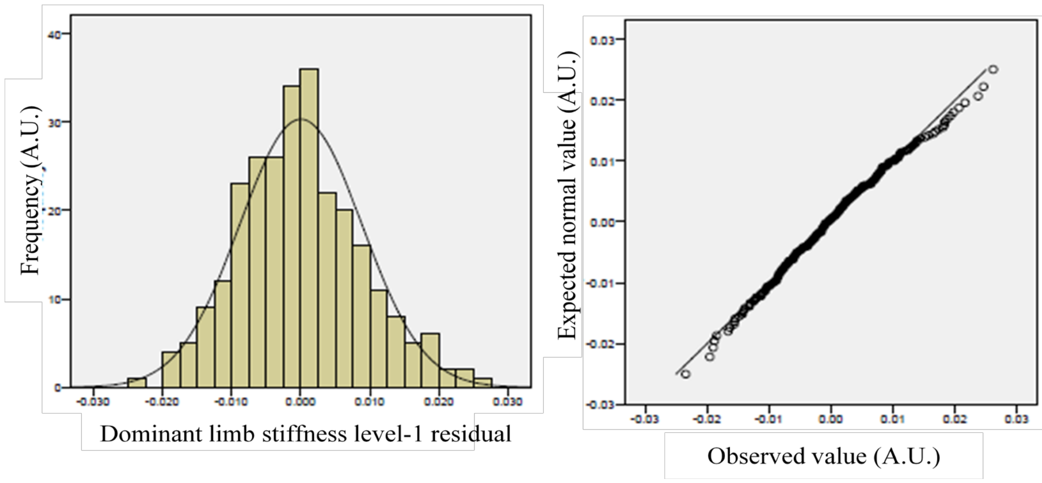


A4: Residual analysis of non-dominant limb cutting performance: Histogram and Q-Q plots

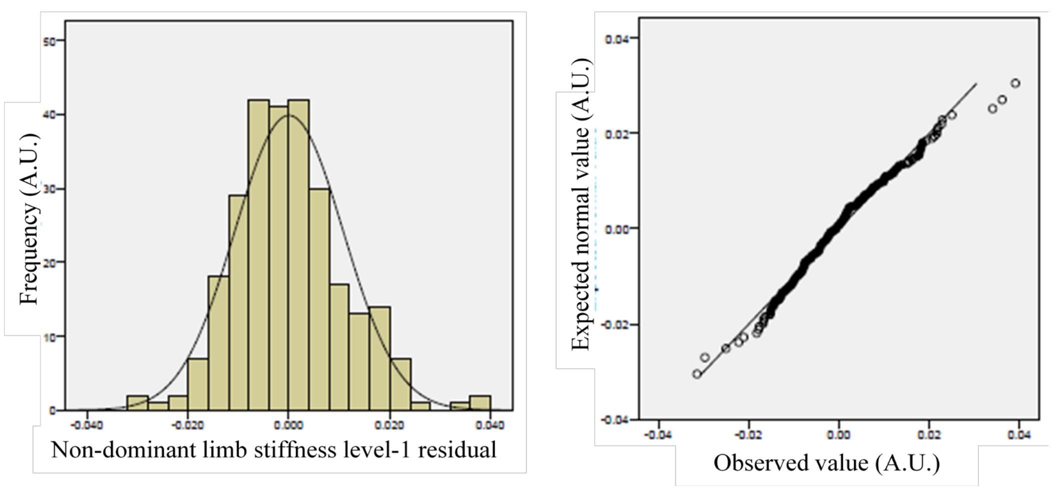




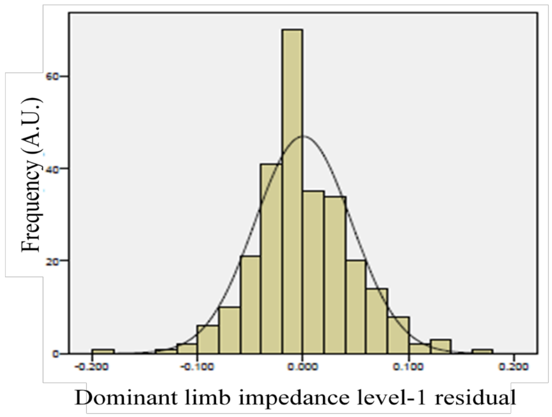
A5: Residual analysis of dominant limb vertical stiffness: Histogram and Q-Q plots

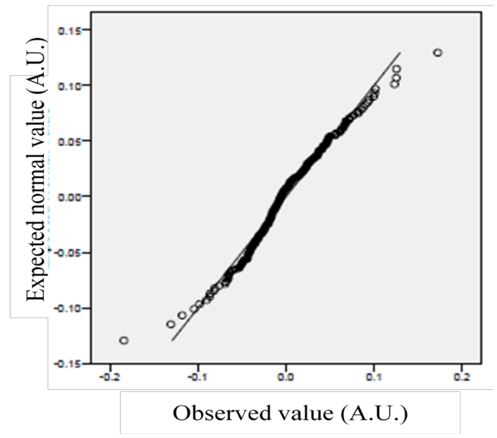


A6: Residual analysis of non-dominant limb vertical stiffness: Histogram and Q-Q plots

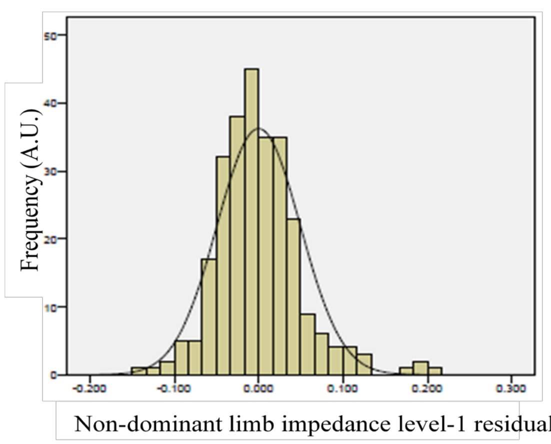


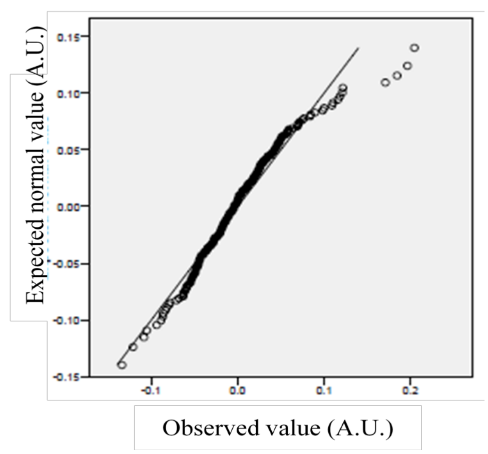
A7: Residual analysis of dominant limb vertical impedance: Histogram and Q-Q plots





A8: Residual analysis of non-dominant limb vertical impedance: Histogram and Q-Q plots





APPENDIX B: HLM DATA ANALYSES OF RPE

B1: Tau as correlations

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	-0.441	1				
TIME_2	**P2**	0.316	-0.914	1			
D	**P3**	-0.577	0.437	-0.449	1		
TXD	**P4**	0.204	-0.5	0.692	-0.567	1	
T_2XD	**P5**	-0.143	0.4	-0.652	0.502	-0.98	1

B2: Reliability estimates (random level-1 coefficient)

INTRCPT1	**P0**	0.746
TIME	**P1**	0.517
TIME_2	**P2**	0.538
D	**P3**	0.506
TXD	**P4**	0.55
T_2XD	**P5**	0.585

B3: Fixed Effects (with robust standard errors)

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	10.89682	0.429123	25.393	23	0
TIME (B10), slope P1	1.348375	0.206562	6.528	23	0
TIME_2 (B20), slope B2	-0.09925	0.030095	-3.298	23	0.004
D (B30), slope P3	3.06904	0.443294	6.923	23	0
TXD (B40), slope P4	-0.92602	0.307054	-3.016	23	0.007
T_2XD (B50), slope P5	0.117775	0.0451	2.611	23	0.016

APPENDIX C: DATA ANALYSES OF SPRINT PERFORMANCE

C1: Tau as correlations

		P0	P1	P2	P3	P4	P5
INTRCPT1	P0	1					
TIME	P1	-0.88	1				
TIME_2	P2	-0.019	-0.974	1			
D	P3	-0.182	0.634	-0.465	1		
TXD	P4	-0.038	-0.618	0.597	-0.691	1	
T_2XD	P5	0.162	0.595	-0.592	0.638	-0.988	1

C2: Reliability estimates (random level-1 coefficient)

INTRCPT1	P0	0.914
TIME	P1	0.504
TIME_2	P2	0.443
D	P3	0.518
TXD	P4	0.373
T_2XD	P5	0.371

C3: Fixed Effects

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	1.621646	0.024731	65.57	23	0
TIME (B10), slope P1	0.030474	0.008159	3.735	23	0.001
TIME_2 (B20), slope B2	-0.00332	0.001245	-2.667	23	0.014
D (B30), slope P3	0.075988	0.014759	5.149	23	0
TXD (B40), slope P4	-0.01528	0.010188	-1.5	23	0.147
T_2XD (B50), slope P5	0.00075	0.001639	0.457	23	0.651

APPENDIX D: DATA ANALYSES OF CUTTING PERFORMANCE

D1: Dominant limb cutting performance

Tau as correlations:

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	-0.234	1				
TIME_2	**P2**	0.125	-0.887	1			
D	**P3**	0.101	-0.321	0.680	1		
TXD	**P4**	-0.293	0.616	-0.801	-0.565	1	
T_2XD	**P5**	0.438	-0.811	0.845	0.422	-0.934	1

Reliability estimates (random level-1 coefficient):

INTRCPT1	**P0**	0.915
TIME	**P1**	0.291
TIME_2	**P2**	0.267
D	**P3**	0.388
TXD	**P4**	0.183
T_2XD	**P5**	0.188

Fixed Effects (with robust standard errors):

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	2.283896	0.032528	70.212	23	0
TIME (B10), slope P1	0.043634	0.008259	5.283	23	0
TIME_2 (B20), slope B2	-0.00519	0.001315	-3.946	23	0.001
D (B30), slope P3	0.068464	0.016584	4.128	23	0
TXD (B40), slope P4	-0.02931	0.01063	-2.757	23	0.012
T_2XD (B50), slope P5	0.00279	0.001726	1.617	23	0.119

D2: Non-dominant limb cutting performance

Tau as correlations:

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	-0.683	1				
TIME_2	**P2**	0.302	-0.789	1			
D	**P3**	-0.272	0.878	-0.763	1		
TXD	**P4**	-0.025	0.007	0.516	0.129	1	
T_2XD	**P5**	-0.026	0.232	-0.736	0.150	-0.957	1

Reliability estimates (random level-1 coefficient):

INTRCPT1	**P0**	0.909
TIME	**P1**	0.18
TIME_2	**P2**	0.342
D	**P3**	0.406
TXD	**P4**	0.399
T_2XD	**P5**	0.439

Fixed Effects:

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	2.3177	0.034139	67.891	23	0
TIME (B10), slope P1	0.031729	0.009027	3.515	23	0.002
TIME_2 (B20), slope B2	-0.00314	0.001638	-1.916	23	0.067
D (B30), slope P3	0.051587	0.018894	2.73	23	0.012
TXD (B40), slope P4	-0.00871	0.014825	-0.587	23	0.562
T_2XD (B50), slope P5	-0.00065	0.002481	-0.263	23	0.795

APPENDIX E: DATA ANALYSES OF JUMP HEIGHT

E1: Squat Jump Height

Tau as correlations:

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	-0.658	1				
TIME_2	**P2**	0.345	-0.926	1			
D	**P3**	-0.406	-0.340	0.567	1		
TXD	**P4**	0.366	0.173	-0.300	-0.906	1	
T_2XD	**P5**	-0.246	-0.143	0.181	0.782	-0.966	1

Reliability estimates:

INTRCPT1	**P0**	0.623
TIME	**P1**	0.153
TIME_2	**P2**	0.144
D	**P3**	0.209
TXD	**P4**	0.288
T_2XD	**P5**	0.347

Fixed Effects:

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	28.555710	1.795535	15.904	23	0.000
TIME (B10), slope P1	0.211427	0.733302	0.288	23	0.776
TIME_2 (B20), slope B2	-0.013676	0.100945	-0.135	23	0.894
D (B30), slope P3	1.642961	1.650563	0.995	23	0.330
TXD (B40), slope P4	-1.344750	1.159961	-1.159	23	0.259
T_2XD (B50), slope P5	0.214684	0.171958	1.248	23	0.225

E2: Modified counter movement jump height

Tau as correlations:

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	-0.530	1				
TIME_2	**P2**	0.505	-0.999	1			
D	**P3**	-0.250	0.473	-0.492	1		
TXD	**P4**	0.474	-0.681	0.692	-0.956	1	
T_2XD	**P5**	-0.516	0.752	-0.761	0.920	-0.994	1

Reliability estimates:

INTRCPT1	**P0**	0.404
TIME	**P1**	0.374
TIME_2	**P2**	0.418
D	**P3**	0.427
TXD	**P4**	0.484
T_2XD	**P5**	0.507

Fixed Effects:

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	27.333259	1.834618	14.899	23	0.000
TIME (B10), slope P1	0.543582	1.239949	0.438	23	0.665
TIME_2 (B20), slope B2	-0.053170	0.186417	-0.285	23	0.778
D (B30), slope P3	1.541264	2.854560	0.540	23	0.594
TXD (B40), slope P4	-0.483947	2.037416	-0.238	23	0.814
T_2XD (B50), slope P5	0.031113	0.295877	0.105	23	0.918

APPENDIX F: DATA ANALYSES OF VERTICAL STIFFNESS

F1: Dominant limb vertical stiffness

Tau as correlations:

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	-0.761	1				
TIME_2	**P2**	0.75	-0.995	1			
D	**P3**	-0.717	0.688	-0.746	1		
TXD	**P4**	0.637	-0.692	0.756	-0.977	1	
T_2XD	**P5**	-0.619	0.664	-0.731	0.972	-0.999	1

Reliability estimates:

INTRCPT1	**P0**	0.635
TIME	**P1**	0.383
TIME_2	**P2**	0.334
D	**P3**	0.372
TXD	**P4**	0.463
T_2XD	**P5**	0.422

Fixed Effects:

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	0.051914	0.006204	8.368	23	0
TIME (B10), slope P1	0.001634	0.003147	0.519	23	0.608
TIME_2 (B20), slope B2	-0.00019	0.000426	-0.449	23	0.657
D (B30), slope P3	-0.00046	0.006787	-0.067	23	0.947
TXD (B40), slope P4	0.000622	0.004854	0.128	23	0.9
T_2XD (B50), slope P5	-7.5E-05	0.000654	-0.115	23	0.91

F2: Non-dominant limb vertical stiffness

Tau as correlations:

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	-0.795	1				
TIME_2	**P2**	0.762	-0.994	1			
D	**P3**	-0.267	0.699	-0.751	1		
TXD	**P4**	0.41	-0.773	0.834	-0.933	1	
T_2XD	**P5**	-0.385	0.723	-0.791	0.921	-0.995	1

Reliability estimates:

INTRCPT1	**P0**	0.566
TIME	**P1**	0.453
TIME_2	**P2**	0.441
D	**P3**	0.22
TXD	**P4**	0.234
T_2XD	**P5**	0.216

Fixed Effects:

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	0.056375	0.006867	8.21	23	0
TIME (B10), slope P1	0.000277	0.004063	0.068	23	0.947
TIME_2 (B20), slope B2	-0.00012	0.000568	-0.211	23	0.835
D (B30), slope P3	-0.00109	0.007314	-0.149	23	0.883
TXD (B40), slope P4	0.002261	0.004845	0.467	23	0.645
T_2XD (B50), slope P5	-0.00023	0.00067	-0.339	23	0.737

APPENDIX G: DATA ANALYSES OF VERTICAL IMPEDANCE

G1: Dominant limb vertical impedance

Tau as correlations:

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	0.013	1				
TIME_2	**P2**	-0.184	-0.984	1			
D	**P3**	0.017	0.926	-0.916	1		
TXD	**P4**	-0.299	-0.943	0.982	-0.850	1	
T_2XD	**P5**	0.446	0.861	-0.928	0.740	-0.980	1

Reliability estimates (random level-1 coefficient):

INTRCPT1	**P0**	0.401
TIME	**P1**	0.281
TIME_2	**P2**	0.225
D	**P3**	0.221
TXD	**P4**	0.206
T_2XD	**P5**	0.204

Fixed Effects:

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	0.232195	0.024252	9.574	23	0
TIME (B10), slope P1	-0.00179	0.014637	-0.123	23	0.904
TIME_2 (B20), slope B2	0.000247	0.001984	0.124	23	0.903
D (B30), slope P3	-0.02853	0.030475	-0.936	23	0.359
TXD (B40), slope P4	0.02491	0.019788	1.259	23	0.221
T_2XD (B50), slope P5	-0.00316	0.002766	-1.141	23	0.266

G2: Non-dominant limb vertical impedance

Tau as correlations:

		P0	P1	P2	P3	P4	P5
INTRCPT1	**P0**	1					
TIME	**P1**	-0.489	1				
TIME_2	**P2**	0.438	-0.971	1			
D	**P3**	-0.526	-0.083	0.219	1		
TXD	**P4**	0.448	-0.128	0.051	-0.885	1	
T_2XD	**P5**	-0.396	0.195	-0.156	0.783	-0.977	1

Reliability estimates (random level-1 coefficient):

INTRCPT1	**P0**	0.556
TIME	**P1**	0.29
TIME_2	**P2**	0.314
D	**P3**	0.496
TXD	**P4**	0.415
T_2XD	**P5**	0.395

Fixed Effects:

Fixed Effect	Coefficient	Error	T-ratio	d.f.	P-value
INTRCPT1 (B00), P0	0.241887	0.032423	7.46	23	0
TIME (B10), slope P1	0.009183	0.016901	0.543	23	0.592
TIME_2 (B20), slope B2	-0.00124	0.00243	-0.512	23	0.613
D (B30), slope P3	-0.02007	0.04414	-0.455	23	0.653
TXD (B40), slope P4	0.021802	0.02682	0.813	23	0.425
T_2XD (B50), slope P5	-0.00302	0.003692	-0.818	23	0.422